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ADVANCED SENSORY SPACECRAFT STRUCTURES WORKSHOP: 10 FEBRUARY 1993

Janet Sater

May 1993

Prepared for
Ballistic Missile Defense Organization

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LtCol Michael Obal of the BMDO Materials & Structures Office sponsored this workshop to define the boundaries for present sensory structures fabrication techniques and performance and to identify issues in the further development of these multifunctional structures. A number of specific issues were identified but only a few are listed here: (1) new design concepts may be needed and multidisciplinary teams are required to integrate electronics with structures; (2) flight tests may be necessary to demonstrate these multifunctional structures; (3) ground qualification testing is an issue since many properties of these structures are as yet unknown; (4) project managers are interested in maximum benefit/risk ratio and will consider these advanced technologies if they provide a mission enabling/enhancing function with minimal impact on system (low risk technology with fail-safe operation); (5) there are strong requirements to address the various "-ilities," especially reliability and especially for electronics; (6) built-in self-testing/health monitoring capabilities are necessary for electronics; (7) practical concerns include, among others, manufacturing and assembly/integration techniques, machinability, data on properties (and performance) of integrated structures, failure mechanisms, interconnects between the electronic packaging and the structure, and cofficient of thermal expansion (CTE) mismatch between the electronics and the structure.

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PREFACE

LtCol Michael Obal of the Strategic Defense Initiative Organization (now Ballistic Missile Defense Organization), Materials and Structures Office, manages a wide variety of advanced technology and demonstration programs addressing needs for various systems. A number of demonstration programs in the area of adaptive structures, particularly for space systems, have been initiated over the past few years. These programs are addressing vibration suppression for improved hit-to-kill performance and on-orbit health and environment monitoring. One sensory structures project, in particular, is demonstrating threat detection capabilities with minimum weight penalty to the spacecraft via attachment of various sensors to its skin. Future efforts along these lines may involve integration of miniaturized avionics packages or other electronic subcomponents into load-bearing structures. The agenda was put together by LtCol Michael Obal, Dr. Chuck Byvik (WJSA), and Dr. Janet M. Sater (IDA) to define the boundaries for present sensory structures fabrication techniques and performance and to identify issues in the further development of these multifunctional structures.

The workshop was hosted by IDA on February 10, 1993. IDA was requested under the BMDO "Materials and Structures Development in Support of the Strategic Defense Initiative" task to participate in the workshop and to prepare a proceedings to document the content of the workshop. This effort was subsequently carried out by Dr. Janet Sater with input from LtCol Michael Obal, Dr. Chuck Byvik, and Mr. Edward Nielsen (WJSA).

ABSTRACT

LtCol Michael Obal of the BMDO Materials and Structures Office sponsored this workshop to define the boundaries for present sensory structures fabrication techniques and performance and to identify issues in the further development of these multifunctional structures. A number of specific issues were identified but only a few are listed here: (1) new design concepts may be needed and multidisciplinary teams are required to integrate electronics with structures; (2) flight tests may be necessary to demonstrate these multifunctional structures; (3) ground qualification testing is an issue since many properties of these structures are as yet unknown; (4) project managers are interested in maximum benefit/risk ratio and will consider these advanced technologies if they provide a mission enabling/enhancing function with minimal impact on system (low risk technology with fail-safe operation); (5) there are strong requirements to address the various "-ilities," especially reliability and especially for electronics; (6) built-in self-testing/health monitoring capabilities are necessary for electronics; (7) practical concerns include, among others, manufacturing and assembly/integration techniques, machinability, data on properties (and performance) of integrated structures, failure mechanisms, interconnects between the electronic packaging and the structure, and cofficient of thermal expansion (CTE) mismatch between the electronics and the structure.

CONTENTS

GLOSSARY

A/D	analog to digital
ACTEX	Advanced Control Technology Experiments I and II
ARPA	Advanced Research Projects Agency
ASIC	Application Specific Integrated Circuit
BMDO	Ballistic Missile Defense Organization
BP	Brilliant Pebbles
CMOS	Complementary Metal-Oxide Semiconductor
CTE	coefficient of thermal expansion
EDU	engineering design unit
EMI	electro-magnetic interaction
FET	field-effect transistor
GNC	guidance, navigation, and control
GSTS	Ground Surveillance and Tracking System
HDI	High Density Integrated
IAPT	Integrated Advanced Power Technologies
IEEE	Institute for Electrical and Electronics Engineers
IPP	Integrated Power Panel
IRAD	Internal Research and Development
JPL	Jet Propulsion Laboratory
KV	kill vehicle
LEO	low Earth orbit
M&S	Materials and Structures
MCM	multichip modules
MMD	micrometeoroid and debris
NRL	Naval Research Laboratory

PCB	printed circuit board
PMAD	power management and distribution
PSI	Physical Sciences, Inc.
PWB	printed wiring board
PZT	lead-zirconate-titanate
QCM	Quartz Crystal Microbalances
RF	radio frequency
RISC	Reduced Instruction Set Chip
RSI	Research Support Instruments
SAMMES	Space Active Modular Materials Experiments
SAWAFE	Satellite Attack Warning and Assessment Flight Experiment
SDIO	Space Defense Initiative Organization
STEP	Space Test Experiment Program
STRV	Space Technology Research Vehicle
TQCM	Temperature-Controlled QCM
VEM	visco-elastic materials
VHDL	Very High Density Logic
WJSA	W. J. Schafer Associates

I. INTRODUCTION

LtCol Michael Obal of the Strategic Defense Initiative Organization (SDIO) [now Ballistic Missile Defense Organization (BMDO)], Materials and Structures (M&S) Office, manages a wide variety of advanced technology and demonstration programs addressing needs for various systems. A number of demonstration programs in the area of adaptive structures, particularly for space systems, have been initiated over the past few years. These programs are addressing vibration suppression for enhanced target tracking (adaptive structures) and on-orbit health and environment monitoring and reporting (sensory structures). One sensory structures project, in particular, is demonstrating threat detection capabilities with minimum weight penalty to the spacecraft via attachment of various sensors to its skin. Further parasitic weight reduction due to elimination of the processor avionics containers and associated cabling will occur when the processor is integrated into a later generation multifunctional panel. Such an approach suggests that additional spacecraft avionics or other electronic subcomponents may be integrable into load-bearing panels. A workshop was proposed in order to define the boundaries for present sensory structures fabrication techniques and performance and to identify issues in the further development of these multifunctional structures.

The Workshop on Advanced Sensory Spacecraft Structures was held at the Institute for Defense Analyses on February 10, 1993. An agenda and list of attendees can be found in Appendix A.

LtCol Michael Obal, Program Manager, opened the meeting by describing the M&S Adaptive Structures program (Appendix B). His remarks also provided an introduction to the workshop. He began by discussing the evolution of BMDO space defense systems from the several hundred kilowatt power levels, hundred thousand pound weights, and several thousand cubic meter structural volumes to the present one kilowatt power, hundred to thousand pound weight, and to few cubic meter volume class of interceptor and surveillance systems. The M&S Program has also evolved in response to the changing requirements (p. B-2): moving from the development of advanced composite materials for stiff, lightweight structures, for example, into proof-of-concept demonstrations, component tests, subsystem demonstrations, brassboard demonstrations, and, finally, ground and flight tests for transition to the BMDO prime contractors.

A driving factor in the Adaptive Structures demonstration programs such as Advanced Control Technology Experiments I and II (ACTEX, pp. B-7 through B-12) has been a significant miniaturization and corresponding federation of control electronics, both of which provide power and weight reductions for the system. This factor is also very important in the development of sensory structures in which sensors, electronics, and structural materials are combined for on-orbit monitoring within given weight, surface area, and volume constraints. Examples of such structures include smart tribomechanisms (pp. B-14 through B-16); Space Active Modular Materials Experiments (SAMMES, pp. B-17 through B-21); and Satellite Attack Warning and Assessment Flight Experiment (SAWAFE, pp. B-22 through B-24).

For the first generation SAWAFE panel, various threat detection sensors are attached to the skin; for the second generation panel, sensors will be integrated with analog to digital (A/D) converters into a skin. A third generation panel may involve integration of the sensors and an A/D converter with the processor. Other satellite avionics or electronic components may be integrable with structure to provide load-bearing capability, thermal control, and radiation and EMI shielding in spacecraft, as illustrated on page B-25. LtCol Obal indicated that what is meant by the term "sensory structures" is, in truth, unknown at this point. However, in order for M&S to spend its dollars most wisely in this research area, an opportunity for industry people to provide input was desirable; thus, this workshop. Perceived benefits from development of this technology--the integration of electronic components into load-bearing structures--include additional design options to further reduce spacecraft weight; reductions in total system cost due to relative ease of manufacturing and assembly; and enhanced survivability in space and threat environments.

Objectives of this workshop were clearly defined:

1. To identify technical issues in the development of load-bearing multifunctional structures that incorporate subsystem avionics within the structural volume;
2. To assess the viability of initiating research efforts in multifunctional structures;
3. To determine the first steps in technology development leading to multifunctional structures; and
4. To suggest near- and far-term applications.

A number of factors to be considered by attendees throughout the day were also highlighted: mechanics issues of embedded electronics in composite structures; spacecraft qualification requirements; assembly and checkout requirements and ground maintainability; fabrication and producibility; and expected failure mechanisms and reliability. Subsystems of potential interest included communications, attitude determination and control, and electrical power, among others. Ted Nye commented that "there may be lots of technologies out there but cost will be critical."

To cover the aforementioned objectives required the participation of several groups of people: experts in spacecraft structural and subsystem design, advanced sensors and actuators, electronics and information packaging, and manufacturers. Summaries of each of the invited presentations and associated comments can be found in Sections II and III. Note that these summaries are not in the order listed on the agenda but have been divided into two subject categories: Design Concepts (Section II) and Applications (Section III).[1] Copies of the charts can be found in Appendixes C and D. Section IV includes the final discussion and summary.

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1 Within each category, presentation summaries follow the order given in the agenda.

II. DESIGN CONCEPTS

A. CHUCK BYVIK, NEW DESIGN CONCEPTS

Chuck Byvik (pp. C-1 through C-11) discussed the evolution of the BMDO systems from the high *volume* requirements for early systems such as the various directed energy weapons and the Boost Surveillance and Tracking System to the high *value* requirements for the current systems such as Brilliant Pebbles and Brilliant Eyes. The figures shown on pages C-3 and C-4 illustrate possible combinations of materials/ properties, production, and structures and can be used to describe the state-of-the-art of available technologies: to do all of these is "unaffordable by many," probably by any. Concurrent with this limitless combination of materials, etc., is a significant growth in computer processing speed.

A logical step may be to integrate historically separate disciplines [i.e., electronics with functional disciplines: with sensors for sensory structures or with optics for silicon (Si) eyes, for example]. In classical optical systems digital processing can be done relatively easily. However, using diffractive optics together with neural network logic and analog signal processing "buys you a skin," a 2500-pixel "eye," for example (p. C-8).[1] The interdisciplinary nature implicit in the development of this technology cannot be overemphasized.

This approach represents a new dimension in integration and may lead to radical new designs (p. C-9). Current spacecraft are designed as endoskeletal systems, having an internal support structure. Future spacecraft may feature exoskeletal designs, similar to insect bodies, where the outer skin is the support structure.

There are two aspects to be considered in the development of this technology: "push" from the technologists and "pull" from the designers. "Push" can occur via appropriately focussed efforts at the technology level. "Pull" from the systems occurs via reduced risk and costs of demonstration to obtain flight heritage for the new technology. It

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1 Jack McKay pointed out that not all optical applications can be addressed via this silicon eye technology as there is a light-gathering resolution limit for large apertures. The Si eye acts as an effective aperture. A good application was thought to be earth or sun sensors--bright objects.

is important that technology demonstrations, such as TechSat or TechShot, be done in a manner that is acceptable to current spacecraft designers.

B. GEORGE FLACH, MULTIFUNCTION STRUCTURES: USE IN MINIMAL QUANTITY SPACECRAFT

George Flach, a designer at the Naval Research Laboratory (NRL), asked and answered a question on the wisdom of incorporating electronics into structural elements: yes, for large volume applications and extremely weight-constrained vehicles, the primary benefit being reduced weight. However, a number of technical challenges were identified (p. C-13):

1. Thermal dissipation is solvable. At the chip level connectors may be necessary to remove heat from the system.
2. EMI ground planes must be designed into the structure from the beginning. The problem is solvable given enough money and time.
3. Schedule impacts are a major concern. People do make mistakes. Additionally, since the structure is now an electronic component, spacecraft fabrication becomes more serial.
4. As a corollary to 3, repair and problem correction during test and integration also become more serial.
5. These complex electronic components/structures will probably not be cost effective if production volumes are low; nor would they be expected to be reproducible.
6. Current assembly techniques are believed to be adequate for adding components to the structure if necessary, though they may not be suitable for completely integrated structures.

His general conclusion was that, for low-volume production and, possibly, low-cost spacecraft or for non-weight-constrained applications, electronics/structural integration was not a good idea. Schedule and cost were stated to be the main drivers in such spacecraft. The money "hump" seems to be a major factor limiting industry acceptance. A company also needs to be able to produce on a reasonable schedule with a reasonably understood budget. One implication appears to be that flaws must be known, a potentially difficult task with these advanced sensory structures given the number of unknowns, at least at present. This fact will drive designers to be more conservative.

A question was raised about built-in health monitoring capabilities for devices. His response was that it was possible but required an up-front investment. There is apparently an Institute for Electrical and Electronics Engineers (IEEE) standard for this: Technology is progressing because the chip manufacturers need it. Lee Robinson stated that it is absolutely necessary for integration of satellites. Another participant commented that capabilities of most of the available avionics were not being fully utilized.

However, given Mr. Flach's conclusion, several potential applications were identified along with a statement that "any flat surface and a supply of money can be made into a[n] electronics and load bearing element." Applications include solar arrays, antenna and antenna electronic functions, functional control or telemetry elements, and optical transmission/processing mixed mode elements.

Spacecraft designers and manufacturers will have additional questions regarding this technology. Issues of concern include dielectric constant as a function of temperature[2] and its uniformity/tailorability; coefficient of thermal expansion (CTE); compatibility with non-outgassing adhesives; machinability;[3] radiation hardness;[4] plating techniques; resistivity; and compatibility with existing fasteners.

C. DON EDBERG, PROGRAM REQUIREMENTS AND TECHNOLOGY INFUSION

Don Edberg (pp. C-19 through C-29) discussed program requirements for implementation of these and, in fact, many other, advanced technologies. From a program perspective, system demonstrations should demonstrate the maximum benefit/risk ratio and mission enabling and/or enhancing functions with minimal impact on other subsystems. Technology development for insertion into such programs should be timely. Apparently, the program people are not interested in parasitic weight when assessing the benefit/risk ratio. In response to a question, Edberg stated that the technologists need to communicate with the systems people from the start of a project; this is beginning to occur in some technology areas.

From a technology perspective, basic and applied research programs (6.1 and 6.2) as well as demonstration and validation (6.3) through ground and flight test programs[5] are necessary. When asked if every technology required a flight test, he replied no. However, in terms of the sensory structures technology, it is believed that flight tests will be required. LtCol Obal commented that current budgets may not allow such testing, in which case it may be possible to design a ground test plan that can test most of the salient features. The

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2 There are reflections with large variations in dielectric constant as f(T).

3 It would be desirable to use common, available tools.

4 Properties can change with increasing radiation exposure.

5 This includes primary flight tests where the technology is a critical part for flight operations and secondary or piggyback flights where it is not.

benefit of a flight test is obvious--it forces problems to be solved on a schedule and it forces a company to show that the devices/structures can be fabricated. Someone commented that even in a flight test, full capabilities of a system are not evaluated. The important part of the flight test process is identifying hard points. In any case, it appears that there is a change in the mindset of government program managers that may require some changes on the part of researchers. In the current budget environment costs typically associated with flight tests may be prohibitive.

Technology insertion should be, of course, the technologist's goal. It implies that the technology is somewhat mature with low risk as demonstrated by extensive ground testing and that it can meet the schedule. It is also desirable that system designers have a sense of ownership of the technology due to their involvement from the beginning. Ground testing should be performed using the same personnel, procedures, and equipment to be used in system acceptance testing. The "-ilities" such as reproducibility and maintainability must be addressed; reliability is particularly important. The most important factor in technology insertion is fail-safe operations: the overall system has to work even if the new technology fails, which initially would seem to imply that it wasn't doing anything. There is, however, built-in redundancy in many systems, particularly for systems using advanced technologies. As an example, there may be five RF antennae; if one fails, the other four presumably will work. But if there is an inherent problem in the design and all five are exactly the same it won't matter that there is redundancy--they will all fail. Therefore, different approaches for the same function may be required to fulfill redundancy needs. Someone raised the question of who in the program chain buys off on the technology, a difficult question when dealing with interdisciplinary efforts as would be the case for these advanced sensory structures.[6] The program manager will probably have to be the one to buy off on this technology, assuming the "trickle-down" theory of technology insertion holds.

An example of an adaptive thermal isolator for the McDonnell Douglas Ground Surveillance and Tracking System (GSTS) design was provided to illustrate these steps (pp. C-23 through C-28). Performance of the baseline titanium structure was compared to that of a composite shell design using lead-zirconate-titanate (PZT) piezoceramic elements and a composite truss design using active struts. Important design concerns were heat flow and vibration suppression. Designers were brought in from the beginning to give them more confidence. In addition to fulfilling the previously mentioned requirements, they

6 In the first place, a truly interdisciplinary team is needed and, at present, there does not seem to be a clear view of what that mix is.

were able to demonstrate that if the electronics failed the system requirements could still be met. Also, the designs were interchangeable so they could be "plugged in" at the last moment.

Concluding remarks emphasized the need for increased communication between systems designers and technologists on several levels: understanding existing systems and system requirements and understanding technology. The technology needs to be low risk with validated fail-safe capabilities. Edberg commented that, in terms of risk, if the goal is to minimize risk to an extreme level the jump with new technology will never be made.

D. LEE ROBINSON, HARDWARE DESIGN PROBLEMS

Lee Robinson discussed hardware design problems (pp. C-30 through C-36). He began his perspective on the problem by stating that, after the proposals are submitted and the dollars are established, a "technology guy" shows some great new technology to a "systems guy" but neglects to show the two 6-ft racks of equipment that go along with it and "therein lies the problem." The systems guy needs to feel that all the problems have been approached by, for example, putting the technology into a flight configuration. While it may not be a law of God, it may be fact of life that for small technical research satellites there is never enough power, packaging volume, mass allotment, or schedule. One approach is to make the systems and equipment smaller, but that doesn't seem to have worked well. Robinson believes that we're "starting out behind the eight ball" and that "we must latch onto things that program managers are interested in as part of technology development."

Difficulties in two areas were addressed, the first being structural actuator amplifier/driver. Major issues include extreme power transfer efficiency, bandwidth/stability requirements, and spacecraft power system isolation/grounding problems. Power transfer from spacecraft power to drivers is a predominant concern since there does not appear to be much proven conversion equipment for space flight with high voltage capabilities. Thermal conductivity paths are likely to be different as well. Actuator bandwidths are wide, which may complicate loop stability designs. The attachment of the devices will also affect their performance: control regimes could be different due to nonlinear behavior. Grounding problems would be complicated by the effects of embedded devices.

A second area of concern was sensors/signal processing with major issues including noise, tracking requirements, and measurements/diagnostics. Noise concerns, both for the sensors and processors, are different due to a change in the environment from a box structure to an embedded one. Tracking refers to the tracking of various performance parameters as functions of changes in environment, i.e., temperature or loads. It will also be important to know how such changes would affect overall stabilities. Built-in diagnostics now become essential: self-health checks would be needed to evaluate changes in performance through manufacturing and assembly. This will also help determine how the structure is to be built and assembled since boundaries/factors affecting device performance will have been identified.

To conclude, Robinson remarked that hardware design and development should be concurrent with system peripheral support functions. An example of superconductivity was used for illustrative purposes: the speed of the developed chips exceeded the ability of the lab equipment to measure it. An ability to check out the appropriate performance/ properties of the device on the ground is essential since one needs to be able to convince the designers that one has a clue as to what is happening. This will be critical for the evaluation of these multifunctional structures. Robinson also believed that the idea of taking laboratory equipment and making it smaller for flight is not viable over the long term. This statement implies an Achilles heel or some inherent physical limitation, according to one attendee. This may not be absolutely true but recognition that the "game changes" is needed. And, finally, time and dollars are necessary to realize actual requirements for applicable and available hardware implementations concurrent with experiment design.

Several questions regarding issues in technology *insertion* were asked of Dr. Robinson, who acts as a liaison between systems and technology at the Jet Propulsion Laboratory. He responded that too many "caverns in the schedule" were not desirable and there should be no technology showstoppers--the more high risk areas there are in a program, the more difficult it is to sell.

E. JACK McKAY, SPACECRAFT MASS MINIMIZATION BY SUBSYSTEM OPTIMIZATION

Jack McKay from Research Support Instruments (RSI) presented a different perspective: RSI, a small company that makes space-qualified, electro-optical instruments works in the envelope of available, off-the-shelf technology and "nuts and bolts" designs. He indicated that the person they would have to convince to use advanced sensory structures technology would be the program manger. Affordability is a critical issue: This technology can't only be used for the space industry; the components must find a larger military and/or commercial market. The basis for his presentation (pp. C-37 through C-43) was work being performed on the SAMMES program with Physical Sciences, Inc. (PSI).

Minimal mass, with or without new technologies, can only be achieved by optimizing the design of a particular system for performance and size (and cost!). There are two approaches to arrive at minimal mass: One is to combine sensors, interface electronics, and structural elements into a single, multifunctional, lightweight component; the other is to package processing electronics into a single, minimal volume block.

In the first case, the sensor/interface circuit support structure must be optimized for maximum strength-to-mass ratio. Additionally, the electronics must have mega-rad radiation survivability capabilities, a major liability. The available selection of extremely rad-hard electronic components is limited. An illustration is provided on page C-39, using a graphite/epoxy frame with flexible circuit faces, similar to a kite.

In the second approach, the electronics must be optimized for maximum functionality per unit volume and mass, possibly via a box enclosure. This permits use of high density, high performance, high functionality integrated circuits that are not necessarily capable of surviving large radiation doses.[7] Such devices might include Application Specific Integrated Circuits (ASICs) and highly integrated micro-controllers. The box can be hidden behind the largest available structural mass for additional protection.

An electronics "brick" is one way to approach building the electronics (p. C-41) and could be used in both approaches. The brick would have a thin skin for EMI protection. The electronic components themselves can provide some radiation shielding as well: intrinsically rad-hard components (i.e., connectors) would be located on the outermost layers, moderately hard components (i.e., line receivers) on the next layers, and least rad-hard components [i.e., high density Complementary Metal-Oxide Semiconductor (CMOS) processors, controllers, other logic devices] in the center. Issues include survival of launch and the ability to manufacture these electronic bricks.

F. BILL KRUG, APPLICATION SPECIFIC INTEGRATED CIRCUIT

Issues associated with ASICs, addressed by Bill Krug from the Naval Air Warfare Center (pp. C-44 through C-50), included Si technologies, techniques and methodologies, embedding processes, and shielding.

Concerns regarding use of Si technologies include life expectancy of the application--months or years; the number needed that determines the most cost-effective technology;[8] the bulk effect since, for 4- to 6-inch diameter Si wafers thicknesses on the order of 15 to 25 mils are required for handling reasons, the ASICs are mostly bulk Si;[9]

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7 These devices can be radiation tolerant to about 10 krads.

8 Analog ASICs are not as mature as digital ASICs, which represent the bulk of the current ASIC market.

9 A charge buildup affects performance. An insulating layer to isolate the electronics from the bulk makes it more radiation tolerant.

ion mobility;[10] and single event upsets.[11] A focused ion beam, used to dope Si, creates quantum wells (deposits impurities) in very specific locations; excess impurities are removed via annealing. Over the years circuit features have undergone significant reductions in size. For example the length of a CMOS transistor gate has decreased from 7.5 μm to 0.7 μm. The active area is about 25 percent the size of the transistor. Feature size affects the operational power and frequency bandwidths. Interestingly enough, there appear to be few organizations in the United States either qualified to fabricate or capable of fabricating these devices: Harris, UTMC, and NSA.

To reduce costs it is critical that the technologies be integrated using computer-aided design approaches first, for worst-case analyses. Synthesis and simulation techniques can then be used to evaluate the designs. For Very High Density Logic (VHDL) circuits, standard cells, and gate arrays there is typically little front end design time. Functional partitioning is another important aspect. This requires decisions regarding what functions are needed; which ones ought to be included, which ones can be included, and how self-testing capabilities can be built into them. Size reduction methodologies consider feature sizes, part count, and pin count. All of these may reduce costs. Reducing pin count increases reliability. At this point questions were raised regarding the mechanics of device testing. Much testing has been done on single crystal Si: mechanical and other properties are known as a function of crystal orientation. Devices are too small to test. Loads on these devices would not typically cause failure as the devices are pretty well-insulated from outside load conditions; it is the bonds that would fail. Therefore, package mounting on the printed circuit board (PCB) is a major issue. At Los Alamos, every transistor is examined layer by layer, gate by gate, a high cost procedure ($10 - $20,000). A related question is as follows: Does enough structural information come with a device that a designer would feel comfortable using it in a structural panel? The response was that if the package conforms to a military specification such information is probably provided. If the package were eliminated, one would have to start from the beginning--design through qualification.

ASICs have been embedded in several ways. In the oil industry a sensor package is placed in a vacuum bottle, a 1-shot deal lasting about 30 minutes. These circuits can also

10 Dopant migration is caused by radiation.

11 Radiation could cause a transistor, for example, to go on or off. This is somewhat an effect of feature size.

be embedded in glass and injected under animal skins for identification purposes.[12] Compatibilities between/among the different materials can be an issue. For example there may be joint degradation due to dissimilar materials; thermal expansion mismatch is another possibility. Materials that are nominally the same may have quite different characteristics, evidence the different background radiation levels in Ohio vs. Chile sand. And, of course, the process parameters (pressure, temperature, layering approaches) under which the devices are assembled will affect their performance.

The amount of shielding required is a function of the desired level of protection. Level of protection can be varied by using different material combinations such as metal-filled composites or woven shield layers. Note that if using graphite/epoxy materials the electronics will require shielding. In addition, it is necessary to know both expected shelf and active/operational lifetimes in order to select the right level of protection.

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[12] This approach is also used for reading license tags at toll booths and is of interest to the auto industry for ID purposes as well.

III. DISCUSSION

A. BILL SAYLOR, SAWAFE AND SMART STRUCTURES PROGRAMS

The SAWAFE1 panel is to be a payload on the Space Test Experiment Program (STEP) 3 flight, a 250-kg TRW satellite with a 500-km orbit. The objective of this M&S-sponsored program at Los Alamos is to develop and demonstrate "smart skins" capable of detecting and assessing laser, RF, and nuclear threats (pp. D-1 through D-10). The skin must be able to define the nature of the attack--where, what, and how much--and provide awareness of tampering using conformal sensors at minimum mass, power, and size, with minimal impact on the host craft. Sensors include laser sensors, a broadband RF antenna, and fiber optics for low-energy X-ray detection. The processor is an experimental one. The panel with sensors will weigh about 3 lb with the processor box weighing about 30 lb (20-60 W peak power).[1]

Future SAWAFE experiments will integrate, first, the A/D converter, and, second, the processor. Weight projections for the second panel and box are about 7-8 lb with 20-30 W peak power. Internal R&D efforts at Los Alamos in the areas of electronics and sensors will be leveraged; miniaturization of the electronics is a key aspect. Issues include material integration, since a conformal panel is the desired end goal, and packaging for the electronics. Packaging needs to be mechanically reliable and have fast turnaround at reasonable costs. An example of the High Density Integrated (HDI) detector electronics modules for the Supercollider was given (p. D-8): these 1" x 2" packages, to be produced in relatively large quantities (thousands), have 1280 input signal channels and can be repaired[2] during manufacture. For the second panel these HDI modules will be attached to the back of the panel to provide a thermal path/radiator with visco-elastic materials for vibration damping and flexible circuit connections. It was suggested that the signal wires between the HDI packages could be embedded so that circuits could just be plugged into panel 2.

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1 Current, off-the-shelf technology would weigh about 100 lb with 100 W peak power.

2 These circuits are built from the back up, starting with bare components and building up the circuit board. Bad layers can be removed but the costs are unknown. It also implies some sort of continuous inspection. It's not yet clear if repairable packages are necessary. It may be more cost effective to replace whole units during flight check-out for the avionics than to repair individual packages.

In terms of check-out and qualification procedures, the need to be able to repair or replace units was identified as desirable. However, replacement of structural parts means that previous functional qualification tests have been invalidated. On-orbit thermal cycling was mentioned as an issue for multichip modules (MCMs). The ability to tweak or adjust these MCMs prior to hermetic sealing is being designed into these devices though it is expected that future efforts will move toward replacement. Using ASICs which are based on the idea of triple redundancy may be more feasible; repairability would not be an issue. A question was asked regarding the odds of getting a factory-produced panel containing everything through a test program. Saylor replied that a production run implies some confidence level, and it usually means quantity.

One major issue was brought up by Jack McKay: radiation and radiation shielding. From a parts selection standpoint there are few electronic components that can withstand high doses of radiation over long periods of time. Shielding could be embedded but such an approach should necessarily be inherent throughout the early design stages. There are basically two alternatives (see Section IIE). The decision on which of the two alternatives will be selected is based somewhat on the mission: if a design requires lots of rad-hard electronics the typical solution is to get them as far away from the skin as possible and shield them in a box. It all depends on how long the owner wants the satellite to survive[3] and how much the satellite costs. If the cost is very low it may not matter. As a point of comparison the current SAMMES electronics would survive about 2 months if it was located on an outer surface.

B. ALLAN BRONOWICKI, SMART PATCH CONCEPT

The Modular Control Patch program (pp. D-11 through D-15) is jointly sponsored by SDI and the Air Force at TRW. The 1" x 2" patch provides retrofittable miniaturized electronics for vibration suppression. It will be space qualifiable and will be capable of adaptive neural control. The patch operates at 80 kHz and includes piezoelectric ceramic sensors and actuators (PZT type), charge amps, analog input/output, and a digital signal processor (33 Mflops) with a serial interface (page D-11). The power converter is capable of driving six patches. The layout of the patch is shown on page D-14. In response to a question, the thermal response of the oscillator was stated to be very stable over the

[3] According to LtCol Obal, the government sometimes has unreasonable or unrealistic lifetime goals for spacecraft.

expected temperature range. The digital signal processor is being hardened[4] by Phillips Lab to address concerns about radiation damage.

An example of a microisolation and pointing experiment is shown on page D-12. According to Allan Bronowicki, micropointing is enabling technology for the Earth Observing System multisensor platform. For this application, the wiring bulk can be eliminated using a multilayer printed flexible circuit tape; the electronics bulk is reduced via multichip modules though parts that require frequent changing are not included in those MCMs. An H-bridge motor driver on a Kevlar-reinforced substrate is being developed for Brilliant Pebbles (BP). The substrate coefficient of thermal expansion (CTE) can be matched to that of Si. Shielding up to 50 krads is apparently designed into this application though survivability is to be demonstrated to 100 krads. TRW expects to go with the equivalent of 200 mils of shielding.

LtCol Obal asked if the approach being taken by M&S to demonstrate these advanced technologies would provide enough data or reduce the risk to an acceptable level for designers or would there be a need to use complete design allowables. According to Allan Bronowicki these demonstrations "will help a lot." However, someone remarked that there was also a need for the government/program managers to say what they think is necessary. Follow-up questions were asked: (1) Would designers be comfortable inserting these patches into a spacecraft if weights and power requirements were very low and if the spacecraft would be fail-safe if these devices failed? and (2) Would it be feasible? Some believed that for large satellites it was probably not an issue. However, another indicated that designs for these large satellites are very conservative and are driven somewhat by limitations on requirements, budgets, contracts, and award fee structures; program managers are often unwilling to add extra items. Schedule was mentioned as a major driver as well. The conclusion seemed to be that designers and Program Offices needed to be involved up front in the evaluation of new technology. The communication void between designers and researchers within the same company was also highlighted.

C. MIKE GALLAGHER, BP LIFEJACKET INTEGRATED STRUCTURAL ELECTRONICS

The Martin Marietta BP program is one of the few current efforts to integrate electronics with structure (pp. D-16 through D-31). This current effort (DD-9 Technology Demonstration) is a product of several past programs: a LightSat IRAD program; several

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[4] The total expected dose is 5 to 10 Mrad. Hardening is accomplished by oxidizing the Si all the way through. The surface will then be annealed, followed by etching of the necessary features.

kill vehicle (KV) flight efforts; and a Reduced Instruction Set Chip (RISC) processor engineering design unit (EDU), the heart of the BP approach. Key areas in the BP design include the RISC processor interface, subsystem control electronics, data distribution, and component integration. For FLT1, due to electro-magnetic interaction (EMI) shielding requirements, ~42 percent of the weight was connectors, ~30 percent was the enclosure, and 26 percent was printed wiring boards (PWBs) and electronics. The weight problem apparently stemmed from the existing culture specifying most of the design and the electronics.

A need for an integrated power distribution and data network was identified, to be accomplished by embedding the salient hardware/software into a lifejacket (LJ) panel while maintaining LJ integrity and configuration control. Goals were to reduce mass, touch labor, required volume, and routing complexity and increase packing density and modularity of the design. Gallagher also indicated that with an embedded system of this type one would be able to check it out earlier in the assembly process.

One of the key areas of application will be for guidance, navigation, and control (GNC, p. D-23). In this phase the GNC components spend most of the on-orbit time waiting for instructions. A couple of examples comparing the conventional approach to that proposed by DD-9 are also provided (pp. D-24 and D-25). The conventional approach involves 2-D electronics, 3-D boxes and cables, low volumetric efficiency, high mass, and complex assembly. The integrated, multidisciplinary approach, on the other hand, involves 3-D microelectronics, 2-D/conformal packaging, high volumetric efficiency, low mass, and modular assembly.

A schematic of the intended layout of the structure can be found on page D-30. Key design issues were launch environment, space environmental effects, platform level autonomy for navigation, power management, and maintenance and producibility. Deliverables include breadboard prototype electronics, ASIC-based input/output for flight designs,[5] an ultra-lightweight power and data distribution network, space qualification tests,[6] and validation of producibility. Requirements include 5 V +/- 15 V, a 50 kHz

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5 One attendee stated that ASICs are high-power processors optimized for electro-optical and knowledge applications; the "last thing it wants to do is fly spacecraft." The ASICs are to be used as programmable interface adaptors for routine spacecraft operations for reduced weight and power reasons. There are actually two prototype steps to be examined before an ASIC is designed on the DD-9 effort.

6 These tests will include the BP boilerplate tests. Whether or not these tests would be appropriate for these integrated panels remains a question; changing the test procedures or even the types of tests because of the way the panels are built may be necessary. According to Gallagher, such changes would require direction from the program office.

control bandwidth, with high-speed digital data transmission. EMI is also a major challenge since it is mostly a black art right now.

Technology shortfalls (risks[7]) requiring particular demonstrations have been identified. These concerns include a lack of data for/quantification of the following: (1) mechanical property characterization of electronic materials and inherent survivability gains, if any, from structural materials; (2) effects of strains (thermal, mechanical) on embedded power distribution networks; (3) removal of excess heat from electronics into the adjacent structure; and (4) interconnects between 3-D packaging and the structural network. The corresponding demonstrations to address these are (1) use of electrical engineering design and analysis tools by mechanical engineers with data transfer capabilities between tools; (2) quantification of electronics performance degradation due to strains; (3) quantification of structural failure modes and lifetimes for structures integrated with electronics; and (4) development of production processes with validation of costs and the "-ilities." Again reliability was identified as particularly critical since existing models will not fit this multi-functional structure technology. A behavioral model of the system is needed for such modeling; without this, it is believed that the design team won't be convinced the problem has been solved.

D. BRIAN MACLEAN, INTEGRATED SYSTEM DAMAGE DETECTION AND ASSESSMENT

The approach of the Martin Marietta efforts, presented by Brian Maclean, for integrated damage detection and assessment on spacecraft (pp. D-32 through D-41) has been to incorporate miniature sensors and advanced multiplexing technology. This also provides health monitoring capabilities for the spacecraft. ARPA is, in fact, sponsoring a program on microelectromechanical systems looking at on-chip data reduction, for example.

For health monitoring, multiplexing is of primary interest. Data are transmitted for all the sensors along a single 3-wire bus embedded in a composite (p. D-34); the design is fundamentally similar to a field-effect transistor (FET). These chip-based microsensors are very sensitive and have a high dynamic range: the sensitivity is 25 A over a 10 kHz bandwidth range. On-board diagnostics and data regression reduce system computational requirements. As an example, a uni-axial strain transducer combines a floating gate FET

7 In this instance, risks are defined by the government program managers. It is necessary for the contractor to show those risks are understood and they can be modeled and predicted, etc. Mike Gallagher commented that it will be impossible, or nearly so, to convince everyone there is no risk.

electric field sensor with an electric field emitter (p. D-35). Changing the FET/emitter spacing allows the sensor to be calibrated for various parameters.

All of these multiplexed sensors combined with a controller and converter[8] can be used to measure a number of different parameters such as strain, flow, and displacement.[9] An example could be alignment between the focal plane array and the inertial measurement unit as a function of manufacturing anomalies, temperature and other environmental factors, and time. The ability to track performance of various systems under these conditions is an advantage of adaptive structures, in general.

Micrometeoroid and debris (MMD) detection addresses the questions of where (impact location), how hard (impact force), and how much damage (flaw size, strain relaxation, induced and shear stress calculations) (pp. D-38 through D-41). Martin Marietta has an IRAD program to develop sensors for this application. Limited testing is planned using graphite/polycyanate panels with a 1-D string of 10 surface-mounted, uni-axial strain sensors; a flexible circuit connects them to the bus. An extensometer sensor to measure absolute displacements is under development. Packaging of the devices for this application is one of the technical challenges. A question was raised as to whether the systems people were interested in MMD detection or not. The initial response was that it could be important in reconfiguring satellite constellations, presumably so that MMD clouds could be avoided; it could also be a point of failure for a single satellite, the apparent conclusion being that there should be interest. According to LtCol Obal, designers did not appear to be generally interested a few years ago, but there may be some applications where MMD damage would be critical.

E. RUSTY SAILORS, INTEGRATED POWER APPROACHES

The Air Force is sponsoring two efforts on integrated power approaches: a contract with Boeing for an Integrated Power Panel (IPP) (pp. D-42 through D-48) and a proposed concept for Integrated Advanced Power Technologies (IAPT) (pp. D-49 through D-53). The IPP combines solar cells,[10] shunt controllers,[11] and dissipators on solar array panels. Additional features include removal of some power processing functions from the bus;

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8 Standard controllers and converters can be used, though on-chip data reduction will provide more information. A variety of sensors can be utilized.

9 ARPA's interest in this program is due to the potential low fabrication costs of these devices. The automotive industry is interested in using these sensor systems for fuel injection systems and for vehicle life determination.

10 GaAs is the solar cell of choice for the moment but other technologies may be inserted as they become available. The operational temperature range of interest is -150 to +125°C. According to Rusty Sailors, the hybrids, etc., have been tested from -160 to +125°C for thousands of cycles on this program. Note that these and the other materials being used are already space qualified.

11 The controllers have been designed to meet high-level radiation requirements.

reduction of thermal management concerns[12] and control and cabling requirements; high modularity[13] and scalability; a reduction of lay-down costs and repair simplification due to the solar cell "ramp" interconnect (p. D-48);[14] no significant reduction in performance with some number of failed hybrids due to inherent fault tolerance and high design redundancy;[15] and emphasis on simplicity and part count reduction.[16] The implication is that the panels must be facing the sun. Sailors replied that the following was the case: When out of the sun, the array shuts itself off and runs by a battery which is charged when in the sun; it boots itself up again when in the sun. This is apparently possible (independent of the bus) since the controller is moved out to the array.

The baseline panel is illustrated on page D-47. It consists of graphite/epoxy facesheets over an Al honeycomb core; a thin layer of dielectric which separates the cover glass/GaAs solar cells from the composite; hybrid drivers, thermal control, and resistor strips, which are located on the backside.

Temperature and radiation are two factors of concern related to potential failures of these solar cell strings. Therefore extensive testing has been performed on these designs to ensure significant design margins exist. From a radiation perspective, for example, transistor gains of 200 can be reduced to 10 before any concerns for the shunt controllers' performance are in order. Performance of a solar cell usually decreases as temperature increases, for another example; this has been addressed from a mission level. Only when excess power exists are the solar cells heated by the resistor strips, so a reduction in their efficiency is not a concern and is actually a positive feature because less power is generated to be shunted. Program emphasis is on ground repair but attempts are being made to address possible failures up front in the trade studies. It may be possible to force the manufacturers/panel suppliers to perform the testing, which may reduce post-assembly testing. However, there would be a cost penalty associated with the panels on such an

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12 This leads to reduced spacecraft bus thermal requirements and reduces the PMAD box count.

13 Modularity implies, to an extent, that multiple mission requirements can be met. In addition, power requirements increases late in the program cause minimal impacts on the PMAD portions of the design, which is not the case in other designs. It would also be possible to feed a primary bus or multiple busses.

14 The wire connects the bottom of one cell to the top of the next. This is, in other designs, one of the concerns for failure; damage to the wire interconnect may cause a disconnect between solar cells. Therefore, significant design and testing has been performed on this increased reliability interconnect.

15 With present technology, replacement of failed solar cells is difficult. Having redundant capabilities may allow flight of failed hybrids; it depends on the specific program and mission.

16 This may lead to lower manufacturing costs and more simple/low-cost testing; solid state processes are significantly simpler, better defined, more repeatable, and less expensive than the hand-made processes for current batteries and the yields are higher as well.

approach, but a great cost benefit from the system perspective. In the end, contractors should be responsible for showing that the device/component/system works as expected.

Thin film technologies integrating power generation (high efficiency solar cells)[17] and conditioning (solid state controller) and energy storage functions (solid state battery)[18] are being considered in the IAPT concept. This concept combines three separately developed technologies into a single package. Perceived benefits include reduction in power system mass and volume; reductions in system and manufacturing process costs; modular interconnects for power bussing; simplified autonomous operation and inherent fault tolerance; and the possibility of remote power. Several schematics showing possible applications are shown on pages D-51 through D-53. One example is the embedding of these IAPT packages in remote sections of the spacecraft to supply low levels of power to sensors.

F. ROY IKEGAMI, STRUCTURALLY INTEGRATED SENSOR TECHNOLOGY

Dr. Ikegami presented an aircraft community perspective on advanced sensory structures (pp. D-54 through D-64). In some sense the aircraft community is bounded by a much tougher constraint since supportability is a critical feature: components must be removable and either repairable or replaceable. Boeing is developing load-bearing structurally integrated antennae/phased arrays. The particular application depicted is a Global Positioning Satellite antenna for aircraft (p. D-56). The antenna is to be conformal with the body contour; and the strength and stiffness of the antenna panel must match that of the surrounding skin. Issues include mechanical properties, some of the "-ilities," EMI and lightning strike protection,[19] and RF distortion at higher frequencies due to structural deformation. Potential cross-talk between elements of the array is being handled via the electronics. The aircraft skin is graphite/epoxy; the antenna panel is fiberglass/epoxy with a copper mesh ground plane; antenna elements are exposed on the surface. Five integration concepts are being examined (p. D-57). Concepts 1, 3, and 5 are conventional: window

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17 The solar cells have efficiencies on the order of 23 to 28 percent.

18 The batteries are conformable; the electrolyte is a thin polymer film, rather than a liquid, and is sandwiched between an anode, a cathode, and two thin metal foil current collectors.. Its performance as a function of temperature is much better than that of $Ni\text{-}H_2$ batteries. Its energy density is 6 times higher than that of $Ni\text{-}H_2$ and 2 times better than that of Na-S. The cost of $Ni\text{-}H_2$ cells ($8-$13,000) is significantly higher than that of a solid state battery as well. The down side is that the solid state batteries are not packaged for space, though Sailors indicated that normal component shielding will adequately address the concern; battery cycling requirements are also an issue, in particular for the cathodes. The Automotive Battery Consortium is very interested in this technology.

19 This would correspond to the charge buildup in space.

frame, non-load-bearing window, and stiffened cavity. The other two innovative approaches--spliced dielectric window[20] and mechanically fastened dielectric window--offer reduced weight and volume; in addition, the avionics are located such that they are insensitive to flight strain. The feasibility of putting the processing electronics in the same region as the load-bearing antenna panel may be examined in future efforts.

Dr. Ikegami identified a number of technical challenges, some similar to those noted previously for spacecraft. The include the following: individual elements move; the elements are physically stressed; they also act as heat sources so cooling may be necessary; elements can be truly conformal but they may point the wrong way; conformation and material, which are not under control of the structural designer, must be part of his design, and thus a multidisciplinary team is needed; integration of these devices must not adversely affect performance of the aircraft (integrity and durability); producibility and supportability[21] are not as good as for conventional technology, and greater lifetimes for avionics components are needed. Having electronics at the back plane represents something of a problem in qualification testing. Typically, over $1 million is spent to determine design allowables for a new material at the coupon level. With embedded electronics it is unknown what those costs would be to develop the same level of design confidence--it remains to be seen whether or not system worth can be demonstrated. Other related concerns included the types of failure that might occur, methods for detection of individual element failure, and methods for detection of effects of structural deformation,[22] believed to be the first step.

Dr. Ikegami identified actions that need to be taken to address four major issues:

(1) Sensor Development: Avionics vendors and materials suppliers should be encouraged to work together.

(2) Integration: Trade-off studies evaluating embedment vs. surface attachment methods are needed; lab tests will be required for validation.

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20 This stepped laminating approach is the lowest weight and volume and allows for easy replacement if necessary. It is also a structural panel. This design turned out to be 61 percent lighter than the best vendor design for a particular aircraft.

21 Pushing avionics vendors to higher reliability is a more difficult problem in the aircraft business for cost reasons: aircraft are typically less expensive than spacecraft. The primary drivers are weight savings and the trade-off of cost with complexity.

22 Development of sensors for this purpose was identified as an enabling technology. Other enabling technologies include load-bearing dielectric window structural integration and electronic module and manifold integrations.

(3) "-ilities": An integrated product development team to aid in design from the beginning is one crucial step here; more reliable avionics are also needed.

(4) Structural Integrity: Fatigue and failure analysis are important; trade-off studies on sensor size and number will be necessary; and combined structural/RF testing will be needed to study effects of deformation on system performance.

These steps need to be accomplished before the technology can be moved toward system demonstrations.

G. TOM VAN ZANDT, MICROSENSORS AND MICROINSTRUMENTS

Tom Van Zandt discussed ongoing efforts at JPL to miniaturize sensors for particular applications (pp. D-65 through D-71). Current sensors have mass, power, and size requirements that are incompatible with many applications, particularly given the drive to smaller satellites.[23] Therefore, miniaturization of these sensors while maintaining the same or better performance is critical. An example of the Mars Environment Survey, to be launched at the turn of the century, was provided (p. D-71). The lander weighs 80 kg (for aerobraking) with ~10 kg for science instruments. Designers would like to get away from boxes and connectors so integrating interfaces will be important. Typically systems engineers will say at the beginning that there is no science mass budget; the ability to do more science using smaller sensors and instruments then becomes quite attractive. Dr. Van Zandt believed that new measurement techniques will be needed since microfabrication techniques alone will not accomplish this goal. These new measurement principles are the focus of the JPL efforts and are aimed at *in situ* science--measurement "right there in the thick of things."

Position sensing technologies developed at JPL were highlighted (pp. D-67 through D-69). One is an electron tunnelling sensor with a sensitivity of 10^{-14} m/Hz$^{1/2}$, useful for alternating current applications above 1 Hz. It works via a flow of electrons through a vacuum gap (on the order of angstroms) between electrodes. A capacitive position sensor having sensitivity of $<10^{-13}$ m/Hz$^{1/2}$ is useful for broadband applications ranging from direct current to 100 kHz. Both of these sensors are 1-D. Multidimensional capacitive-based edge sensors are used for precise measurement of relative displacements and rotations.

A number of applications for these sensors were also identified. Only a few will be highlighted here. The tunnel sensors have been demonstrated in an uncooled IR detector--a

23 This means a different launch vehicle class can be used and launch costs can be lowered.

Golay cell, a sort of inverted electron tunnelling microscope. This is a broadband application. The noise equivalent power is 2 x 10^{-10} W/Hz$^{1/2}$. Apparently a pinhole in the device acts like a high bandpass filter. Another example is the broadband capacitive accelerometer[24] which can be used as a seismometer, microgravity accelerometer, or for orbital diagnostics. For seismometer applications the noise floor is at the nano/Hz$^{1/2}$ level. These devices can be made cheaper and 50 times smaller than the current technology sensors. They must be well-coupled to bedrock on earth via earth penetrators (reentry vehicles?). Someone asked if current efforts were directed at more sensor development or flight of existing sensors. According to Van Zandt, the present budget environment necessitates an emphasis on flight heritage for these sensors.

The main technical issue in terms of sensory structures was the need to develop microsensors for use in constrained applications; high-sensitivity microsensors would be critical, enabling technology in such cases. As a corollary, research into fundamental measurement techniques is also deemed important. The push for such developments should, in addition, be oriented to particular applications. A bottom-up approach to develop sensors was thought by Van Zandt to be a logical approach in the design/development of sensory structures. In that case it is important to first determine what is to be sensed; decide if it's practical/possible; determine the availability of sensors; and perform sensor development work as needed. Then, system engineering and integration issues can be addressed.

H. TED NYE, NEW DESIGN TECHNOLOGIES

TRW has been involved in the development of several technologies for consideration in the design of sensory structures (pp. D-72 through D-88). These include an electrochromic sail, hairy visco-elastic materials (VEMs), piezoceramic shaping, and smart healing structures.

An electrochromic sail could be used to perform satellite steering via solar pressure (pp. D-73 through D-75). These devices change their optical properties as a function of applied electric potentials. The designs are simple with no moving parts and potentially low cost; they are also low power (~1 W), low voltage (~1.2 V), and lightweight.[25] Since the panel acts like a capacitor it needs to be charged up periodically, about every 24 hours. Some environmental tests have been performed to examine electro-optical behavior as a

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24 Apparently there is a possibility for over-ranging with these devices due to a sensitivity to very high loads. Some sort of physical stop or cage may be required. No shock testing has been performed yet.

25 Steering a BP requires a panel on the order of 1 to 2 m^2.

function of temperature, ultra-violet and other radiation exposure. Ted Nye indicated that this material could be utilized on ACTEX II at no cost; it may be possible to determine the pressure based on the PZT response. The competing devices are more complex and include magnetic torque rods, momentum wheel devices, and propulsion systems.

The hairy VEMs, illustrated on page D-76, consist of VEMs with embedded, chopped fibers that act as a pseudo-constrained layer. Energy is dissipated though fiber interactions with more efficient load transfer to the VEM; these hairy VEMs seem to work best in bending. It is believed that these materials could be used to knock down acoustic vibration and may be applicable to small spacecraft. Temperature sensitivity of the VEMs remains a major problem as do mass production techniques. Experimental parameters that have been considered include fiber aspect ratios,[26] volume fraction and orientation of fibers, and damping as a function of temperature and fiber aspect ratio; use of several different fibers together has not been examined.

Limitations with current piezoceramic materials include thickness (<5 mils desirable), shape (curved pieces desirable), material aging (reduced/no loss of properties over time desirable), and poling direction (poling along length rather than thickness desirable). Though the materials are being utilized within these constraints, these limitations are believed to cause expensive, work-around solutions and reduced performance. Further developments are required. Some of these issues are, in fact, beginning to be addressed in a small M&S-sponsored program through NRL with Dr. Manfred Kahn.

In some very preliminary studies TRW has been investigating smart strut concepts to detect, locate, and repair structural faults. Faults are detectable via several methods: resonant frequency changes (stiffness degradation), increased damping (delaminations), and poor coherence transfer functions (loose joints). These are illustrated on pages D-82 through D-86. The idea behind the smart strut is analogous to a human lymph node system: embedded piezoceramics would provide "muscle" action to bleed internally located but unmixed epoxies into damaged areas of the structure. The epoxy would probably be low viscosity, similar to water. As shown on page D-87, a two-part tubing network would be embedded with the piezoceramics; adhesive pumping, activated following some system/health identification, would be locally controlled. While it is possible to detect, quantify, and locate damage, the smart healing strut technology is in the concept stage only.

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[26] Fibers are coated first, then chopped.

It has been demonstrated for concrete structures, however. This technology may also be applicable to liquid-lubricated tribomechanisms.

I. PRAKOSH JOSHI, AN INTEGRATED SENSOR/ELECTRONICS PANEL FOR SPACECRAFT ENVIRONMENT MONITORING

Physical Sciences is the prime contractor for the M&S SAMMES program (pp. D-89 through D-103). One of the program objectives is to characterize the low Earth orbit (LEO) environment--atomic oxygen, contamination, solar radiation, trapped radiation, and thermal cycling--at specific locations on the spacecraft. Sensors on the current version include actinometers, Quartz Crystal Microbalances (QCMs), Temperature-Controlled QCMs (TQCMs), sun sensors, radiation sensors, and thermocouples. Illustrated on pages D-91 through D-92, it weighs 2.8 kg and is contained in a 3500 cm^3 volume; power demand for the electronics is 5 W. The desired lifetime is 3 years at 1000 km. The remainder of Prakosh Joshi's presentation was a case study for multifunctional structures based on the SAMMES module, still maintaining its functional/performance characteristics and addressing design changes, technology limitations, risks, and costs.

In the conceptual design several steps were considered: elimination of the metal housing which is 35 percent of the LEO weight; redesign of the electronics, which are 45 percent of the LEO weight, for radiation hardness; miniaturization/integration of the electronics into ASICs (pp. D-95 and D-96); modification of QCM and calorimeter designs (p. D-97);[27] analysis of the structural response of the G-10 printed circuit board (PCB) with embedded sensors/electronics (p. D-99); and evaluation of thermal control aspects. The estimated total weight for the redesigned panel, 7.5" x 6.5" x 0.79" thick, is 760 gm.[28] This panel weight includes the PCB, components (electronic?), two TQCMs, three calorimeters, five actinometers, solder/conformal coating, silver/teflon film, and assorted hardware. The maximum power is 7.3 W: 2.5 W for the electronics, 4.8 W for the Peltier cooler needed for the QCMs. Structural response was also determined: 167 Hz natural frequency, 1520 lb minimum buckling load, maximum stress and displacement of 4925 psi and 0.022 in., respectively.[29] In terms of thermal response Dr. Joshi believed it may be

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27 The QCM is modified at the expense of power. The calorimeter is not affected by radiation and can be miniaturized.

28 This weight does not include the power supply. It may be possible to make the support panel thickness, 0.20 inches in this design, smaller.

29 Stress and displacement are determined from the SAMMES protoflight vibration spectrum with a factor of safety = 7.

necessary to provide additional conduction to the spacecraft (p. D-101). In addition, heat pipes may be needed to control QCM cooling to <-25°C.

So, with these changes what has been gained? Performance gains/losses include a 70 percent weight reduction; a 50 percent operating power reduction, though at a sacrifice of the quiescent (low power) mode of the current design; operation at higher altitudes and in more hostile environments due to an increase in radiation hardness of the electronics to 80 krads;[30] and a loss in controllability of cooling QCMs. EMI susceptibility has not been evaluated yet. For more effective heat conduction to the spacecraft the PCB must have a ground plane >5 mils thick. Heat pipes may have a weight impact on the system; in addition, it's not clear what types and geometries would be appropriate for this application. Cost issues are of some concern as well. Development tools and nonrecurring costs for ASICs are high ($\$10^5$ levels[31]) though reproduction costs may be more reasonable ($\$10^2$ levels). It is likely that integration will be relatively simple and costs will be low. Reduction in space qualification test costs is not clear at this point; sample testing from a lot may be adequate after full qualification testing of the first few panels, but it may not. It is also not clear when such testing would be performed and by whom.

30 The transformer limits the radiation hardness to 80 krads. Other components are hardened to 1 Mrad.

31 This is a Harris number. At TRW the price mentioned was at $\$10^7$ levels.

IV. DISCUSSION AND SUMMARY

A. DISCUSSION

The discussion following the presentations covered a wide variety of topics. They are addressed in chronological order in this section. LtCol Obal commented that there did not seem to be any physics barriers that would be major showstoppers in the development of these multifunctional structures. There were some very difficult engineering issues to be addressed, however. The approach to solving some of them could be similar to that used in the design of conventional avionics.[1] Some of the structures in the process of being designed/built (e.g., SAWAFE, BP lifejacket) were not truly integrated though fairly significant steps toward that goal were being made. A multifunctional panel concept involving an RF system for satellites has been briefed to NRL. They seem to be very excited about the technical possibilities:[2] such a panel may be amenable to basic operations for all spacecraft.

The issue of communication among the right groups was brought up several times. Multidisciplinary teams, including the Program Offices, are necessary from the beginning for successful integration. Two communication paths are important: one between technologists and systems people in the same field (interprofessional) and another between technologists and systems people in different fields.

Link margins, data rates, and standardization were discussed briefly. One attendee commented that more power is always needed to close the link margin. Frequency allocations are never received until late in the design; therefore, the system needs to be programmable. A range of transmitters are being developed to cover higher bandwidths. Apparently there is lots of standardization going on now.

The Brilliant Pebbles program was identified as "a nice first attempt." The designers will have to address all concerns to satisfy the BP program managers. A "snap-together" approach is needed.

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1 Environmental factors of concern include EMI, thermal balance, and radiation, the most critical.

2 According to NRL, these RF systems are always expensive, they're always delivered late, and they never work. (An exaggeration, perhaps?)

Several people commented that development of this technology for one or two spacecraft did not really make sense. Large-volume applications, not limited to space, are necessary from a cost standpoint.

Miniaturization of electronics continues to be a key driver in the development of this technology.

Rusty Sailors mentioned the book *U.S. Competitiveness in Space Power*, in which competition from Europe and the Pacific Rim countries is highlighted. It is believed that the Pacific Rim countries "will figure out a way to do this."

LtCol Obal discussed the joint BMDO/UK STRV-1B (Space Technology Research Vehicle) flight experiment that contains 14 subexperiments. The subexperiments are packed into a small space using current technology (apparently a "spaghetti" wiring nightmare). In some cases a backplane is being used as structure. Local shielding is used in each module as appropriate. Each board has individual thermal and power requirements, so adequate volume must be provided.

Current space systems are optimized for delivery and cost. It was felt by some that the focus should be customizing the payload rather than customizing the system.

A bigger box may be more weight efficient and have fewer connectors. However, one has to be able to test it; and it may be that one big box is more of a problem than several small boxes.

Standard interfaces are being examined.

The concept of line-replaceable units such as is of interest to the aircraft industry is an intermediate step in the development of multifunctional structures. The IRIDIUM spacecraft program is apparently using this concept.

And, finally, several concluded that these panels would probably have to be flown on large spacecraft first. That would give more confidence to and gain the interest of small satellite designers/manufacturers.

B. SUMMARY

Major points from the workshop can be summarized as follows:[3]

1. Miniaturization of electronics and federation of control electronics have been key factors in the development of adaptive/sensory structures to date.

2. New design concepts may be needed to integrate electronics with structures since the old conventional way may not work. The BP program is an example. The conventional approach[4] involves 2-D electronics, 3-D boxes and cables, low volumetric efficiency, and high mass with complex assembly; the new approach involves 3-D electronics, 2-D conformal packaging, high volumetric efficiency, and low mass with modular assembly. Modular assembly implies easier repair/replacement procedures.

3. Multidisciplinary teams, including the Program Offices, are necessary from the beginning for successful integration. Two communication paths are important: that between technologists and systems people in the same field (interprofessional) and that between technologists and systems people in different fields. There seemed to be general agreement that systems people need a sense of ownership of the technology; their involvement from the start of a technology development program will help pull the technology into application.

4. Flight tests like those for TechSat or TechShot may be necessary to demonstrate these multifunctional structures. Ground qualification testing is an issue since many properties of these structures are as yet unknown. Therefore, there is a strong need to develop system peripheral support functions to be able to measure the performance of these sensory structures on the ground.

5. Schedule and any associated cost impacts are major drivers in spacecraft programs since many systems are driven by schedule. With advanced sensory structures, fabrication would become more serial, more similar to that for electronics. This, in turn, means repair/replacement of components during test and integration is more serial.[5]

6. Cost is not a major consideration for spacecraft designers, according to some. It *is* according to others. In any case, high-volume applications are necessary to reduce costs for these multifunctional structures.

---

3 I have attempted to address these from the most general to the most specific, i.e., general design concepts to specific materials compatibility issues.

4 Note that current structures are designed with high safety factors to meet launch and operational environments/conditions.

5 Note that "replacement" means previous functional qualification tests are probably invalidated.

7. Project managers are the ones who have to buy off on the technology. They are interested in maximum benefit/risk ratio. Advanced technologies will be considered if they have a mission enabling/enhancing function with minimal impact on system. This usually means low-risk technology; fail-safe operation is critical.

8. There are strong requirements to address the various "-ilities," especially reliability and especially for electronics. This can be accomplished via redundancy using different approaches for the same function. It may also be possible to require the manufacturers to do more testing. The group generally concluded that built-in self-testing/health monitoring capabilities are necessary for electronics.

9. In general, high-speed, low-power, all-purpose processors are available. In most applications capabilities of the current devices are not fully utilized. Cost is one consideration in the selection of appropriate electronics technology: digital ASICs are mature, analog ASICs are not.

10. Elimination of the electronics packaging will probably mean starting from the beginning--from design through qualification. At this time there are no military specifications addressing such a situation as is likely to occur with these fully integrated structures.

11. New measurement techniques are needed for sensors since microfabrication will only get you so far. Microsensors need to be developed specifically for constrained applications. A bottom-up approach to design starting with sensors may be appropriate: determine what is to be sensed; decide if it's practical/possible; assess the availability of sensors; and develop sensors as needed.

12. The issue of compatibility of structural materials with electronics concerns more of the practical side of the development of multifunctional structures. Specific relevant items to be addressed that were identified in this workshop include the following: manufacturing and assembly/integration techniques; machinability; data on properties (and performance) of integrated structures; survivability during launch and under operational/environmental conditions;[6] effects of strains on performance; failure mechanisms; interconnects between the electronic packaging and the structure; CTE mismatch between the electronics and the structure; heat removal from electronics; cross-talk between devices.

---

6 Radiation was identified as a particularly critical problem for electronics. The selection of extremely rad-hard components is quite limited at this time.

APPENDIX A

AGENDA AND LIST OF ATTENDEES

Workshop on Advanced Sensory Spacecraft Structures
February 10, 1993

Agenda

7:45 am	Begin check-in, coffee, etc.	
8:05	Welcome	J.M. Sater, IDA
8:10	Introduction	LtCol M. Obal, SDIO
8:30	New Design Concepts	C. Byvik, WJSA
8:50	SAWAFE/Smart Skin	W. Saylor, LANL
9:20	Smart Patch	A. Bronowicki, TRW
9:40	Multi-Function Structures: Use in Minimal Quantity Spacecraft	G. Flach, NRL
10:00	Break	
10:20	Program Requirements & Acceptance	A. Bicos, McDonnell Douglas Aerospace
10:40	Hardware Design Problems	L. Robinson, JPL
11:20	Integrated Structure/Electronics	M. Gallagher, Martin Marietta
11:40	Integrated System for Damage Detection and Assessment	M. Misra, Martin Marietta
12:00 pm	Lunch	

1:00		M. Robyn, Aerospace
1:20	Integrated Advanced Power Technologies	R. Sailors, Aerospace
1:40	Structurally Integrated Sensor Technology	R. Ikegami, Boeing Defense & Space
2:00	Microsensors and Microactuators	T. Van Zandt, JPL
2:20	New Design Technologies	T. Nye, TRW
2:40	Spacecraft Mass Minimization by Subsystem Optimization	J. McKay, Research Support Instruments
3:00	An Integrated Sensor/Electronics Panel for Spacecraft Environment Monitoring	P. Joshi, Physical Sciences Inc.
3:20	ASICs	W. Krug, Naval Air Warfare Center
3:40	Break	
4:00	Discussion and Closing Remarks	All

Dinner on your own at Hamburger Hamlet, across the street from IDA.

Workshop Attendees

Bill Saylor Los Alamos National Laboratory P.O. Box 1663, MS D448 Los Alamos, NM 87545	505-665-5709 fax 505-665-4657
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Mohan Misra, Brian Maclean/Mike Gallagher Martin Marietta Box 179, MS/B3085 Denver, CO	303-971-9390 fax 303-971-9141
Roy Ikegami/Sherm Bigelow Boeing Defense & Space Group P.O. Box 3999 MS 82-97 Seattle, WA 98124-2499	206-773-5876 fax 206-773-4946
George Flach Naval Research Laboratory Code 8130 Washington, DC 20375-5000	202-767-6100 fax 202-767-1952
Lee Robinson Jet Propulsion Laboratory 4800 Oak Grove Drive M/S-138-212 Pasadena, CA 91109-8099	818-354-2680 fax 818-354-4919
Carl Kukanan/Tom Van Zandt Jet Propulsion Laboratory MS 180-604 4800 Oak Grove Drive Pasadena, CA 91109-8099	818-354-4814/5389 fax 818-393-5269/5143
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McDonnell Douglas Aerospace
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Kirby Barnett/Bill Krug
Naval Air Warfare Center
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Indianapolis, IN 46219-2189
317-351-4597/7964
fax 317-351-4491/3690

Other:

LtCol Mike Obal
Chuck Byvik
Janet Sater
Alok Das
Edward Nielsen

APPENDIX B

INTRODUCTION TO THE WORKSHOP ON ADVANCED SENSORY STRUCTURES

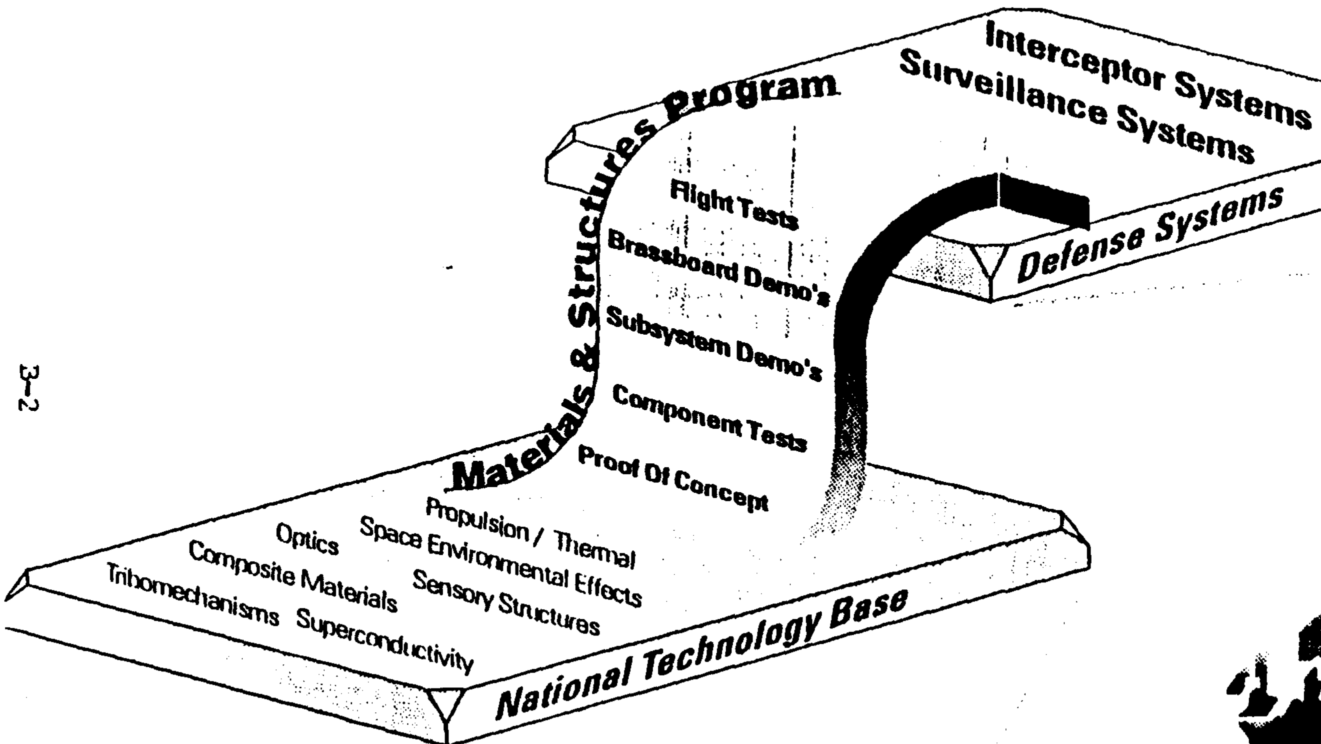
Workshop on
Advanced Sensory Spacecraft Structures

LtCol Michael Obal
SDIO M&S Program Manager

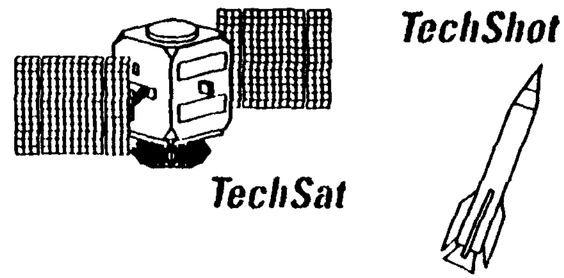
February 10, 1993

JMS/dls:1
1/22/93

M&S Program Evolution



Technology Flight Demo's

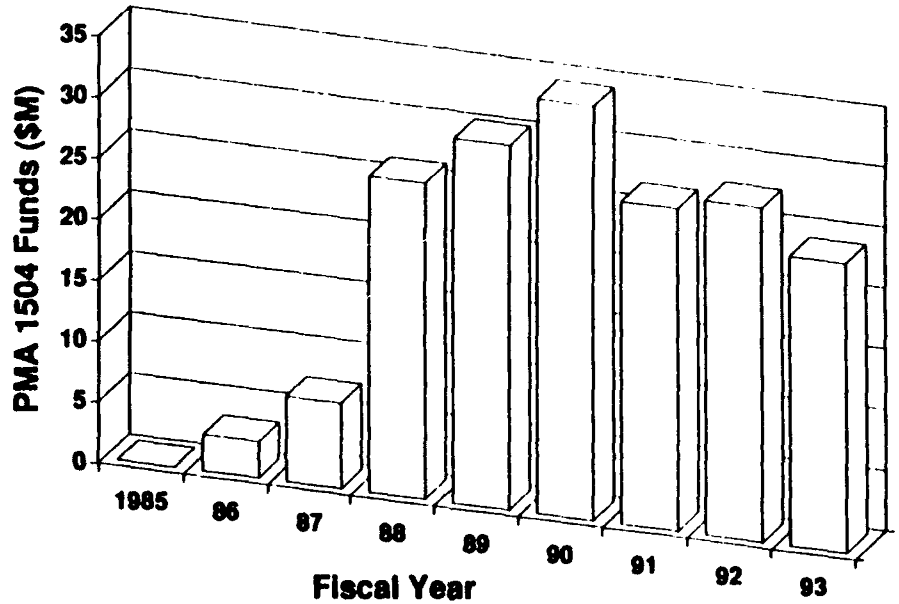


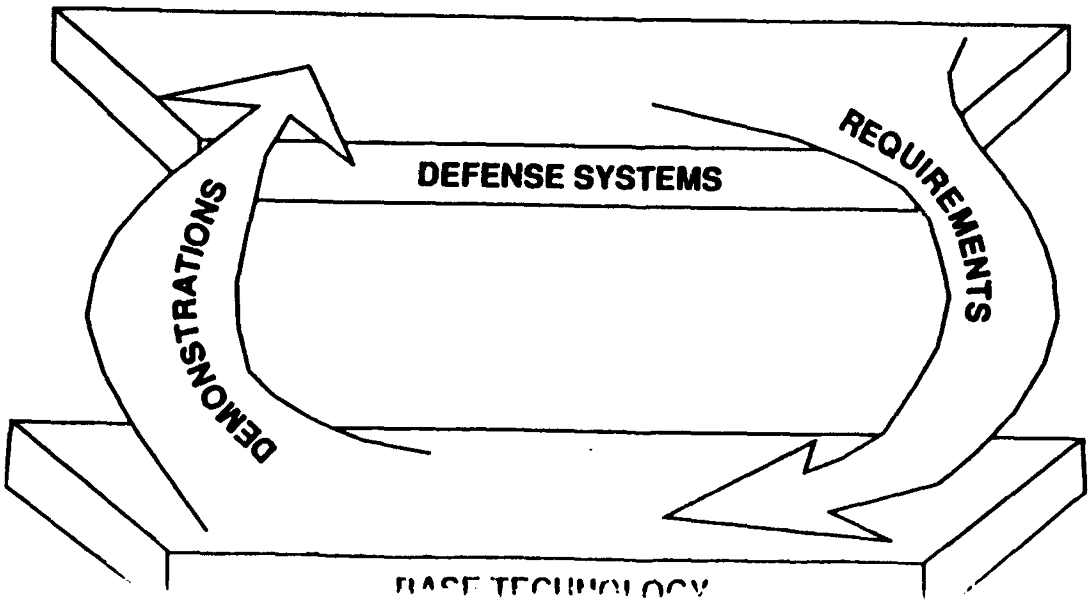
M & S Program Areas

- *Adaptive Structures*
- *Space Evironmental Effects*
- *Lightweight Structural Materials*
- *Optical Materials*
- *Tribomechanisms*
- *Propulsion/Thermal*
- *Superconductivity*

24001

M&S FUNDING HISTORY



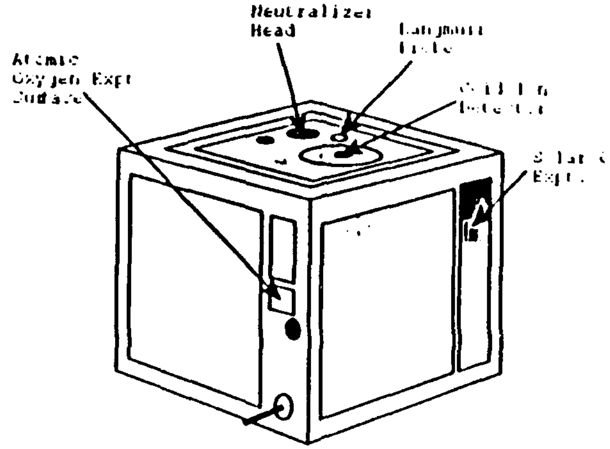


Materials & Structures PMA 1504

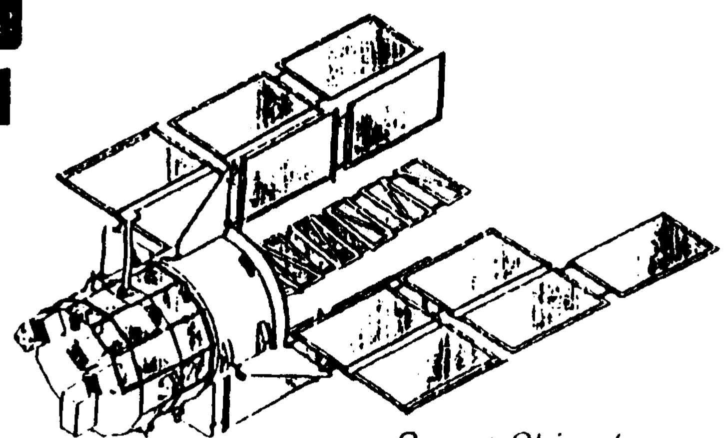
Adaptive Structures

Provide Active / Passive Vibration Suppression Technology to Reduce Sensor Jitter and Enhance Surveillance Pointing Tracking Systems. Provide Structures for On–Orbit Health Monitoring & Detection.

US/UK STRV–1B
Cryocooler Isolation Flight Test

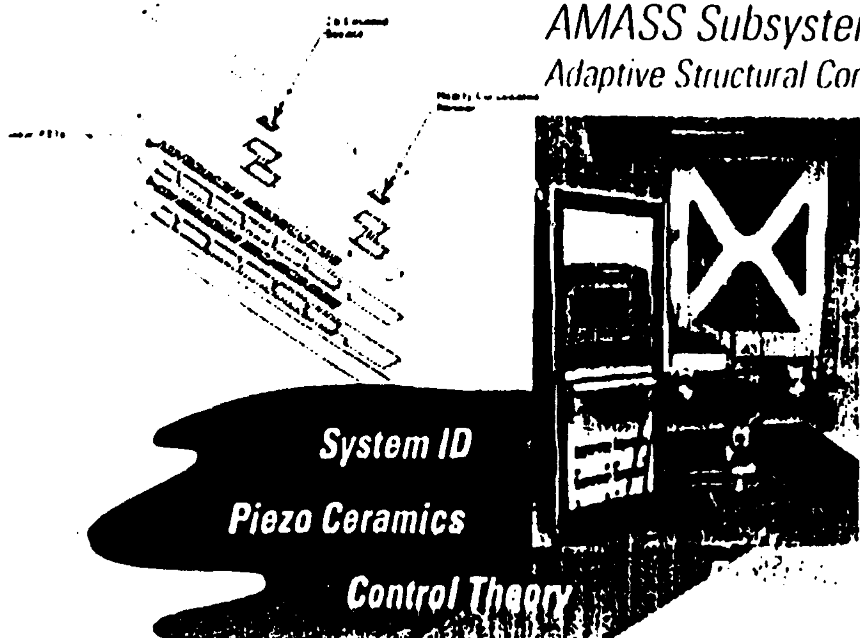


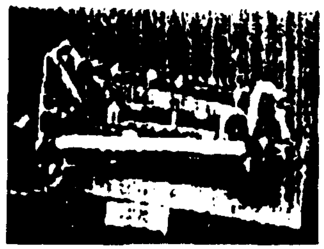
US/Japan Flight Test
Active Alignment Optical Platform



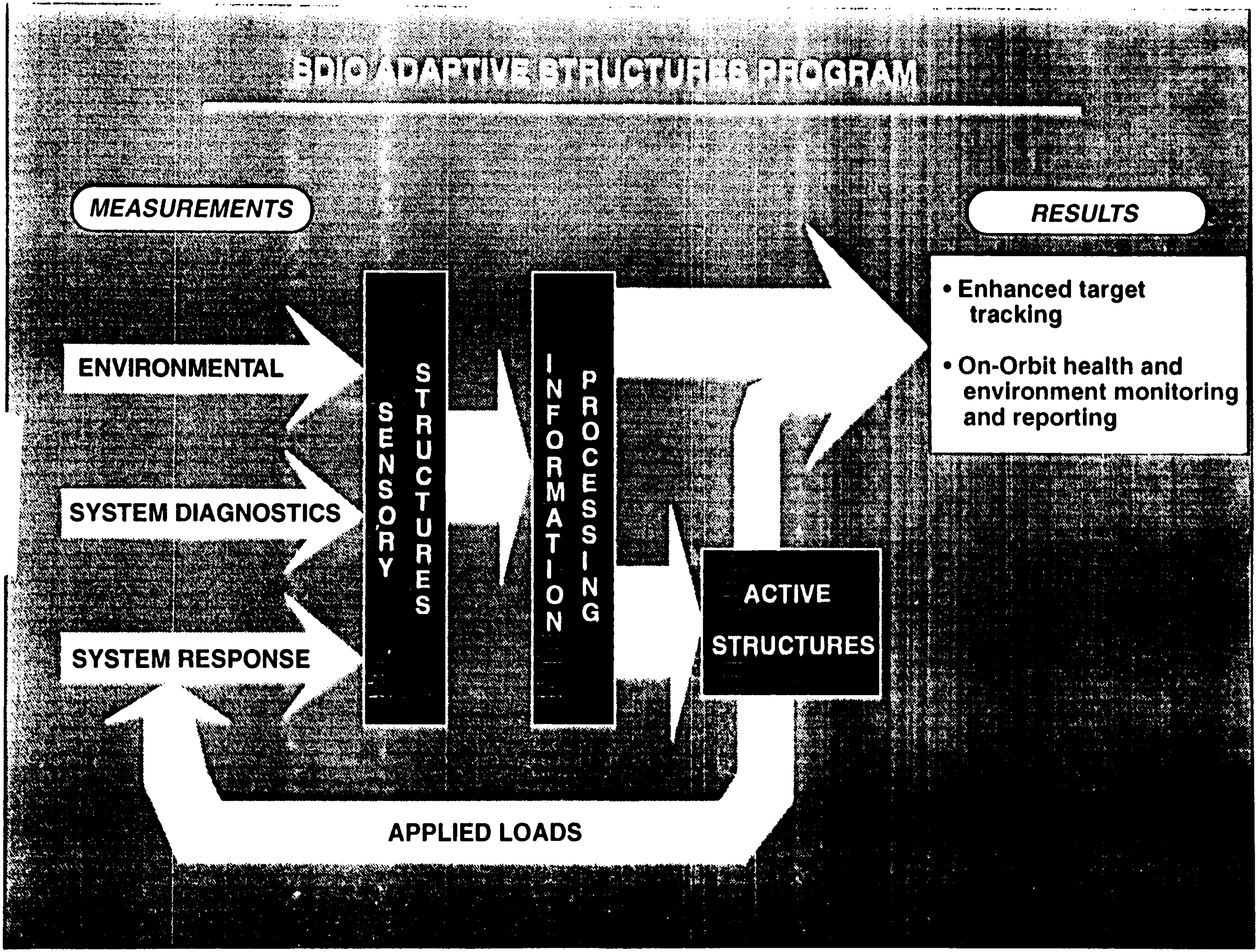
Smart Skins/
Adaptive Structures
Flight Test

AMASS Subsystem Test
Adaptive Structural Component Fab





Actex–1
Demo On-Orbit
Durability/Adaptive Control


SDIO ADAPTIVE STRUCTURES PROGRAM
MEASUREMENTS
ENVIRONMENTAL
SYSTEM DIAGNOSTICS
SYSTEM RESPONSE
SENSORY STRUCTURES
INFORMATION PROCESSING
ACTIVE STRUCTURES
APPLIED LOADS
RESULTS
• Enhanced target tracking
• On-Orbit health and environment monitoring and reporting

Enhanced Target Tracking Performance

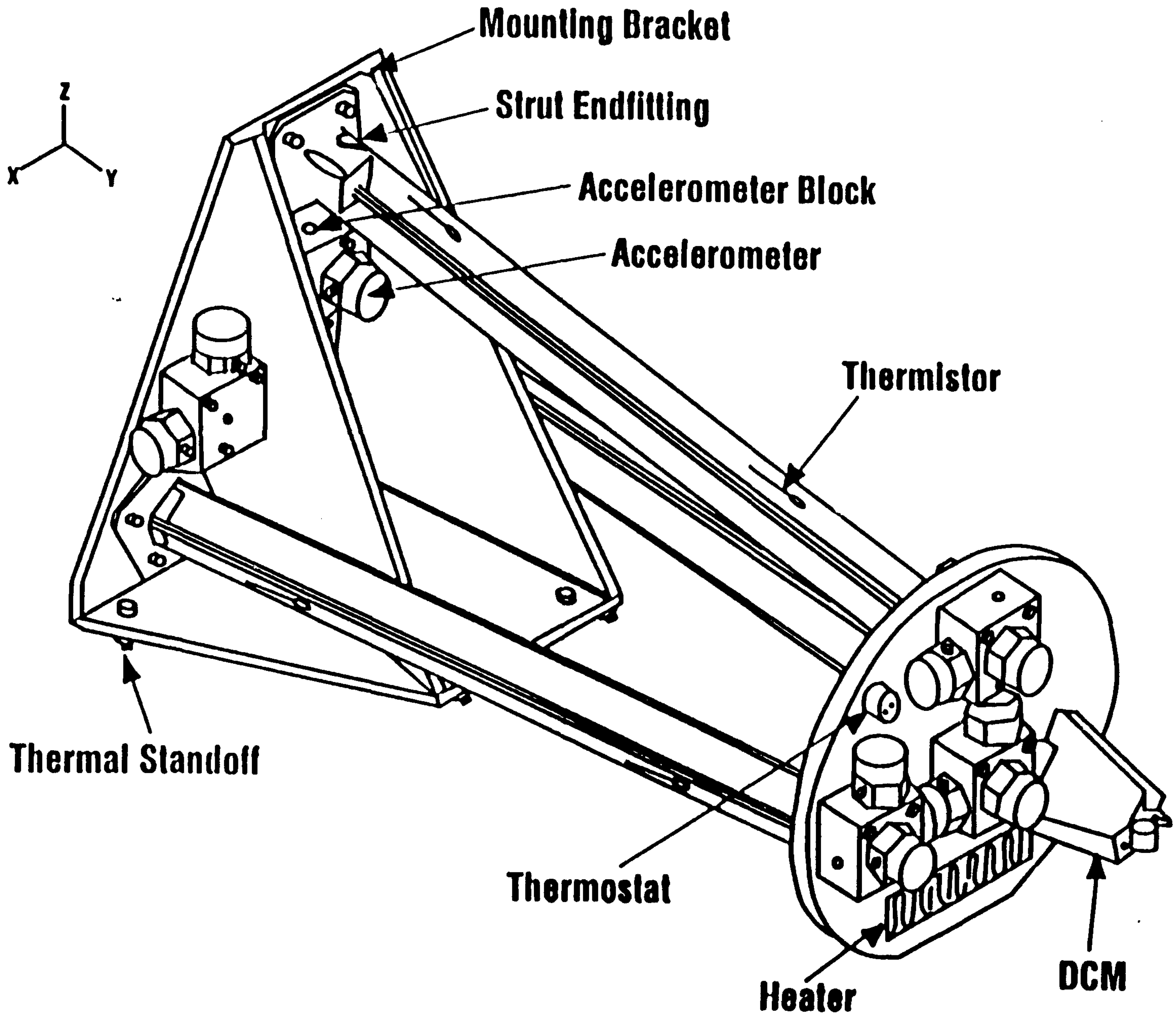
Goal

- Provide a means for adaptive jitter control for space-based pointing and tracking systems
  - Correct misalignments and/or model uncertainties
  - Eliminate external optical system disturbances
  - Recover environmental or threat damage effects

Approach

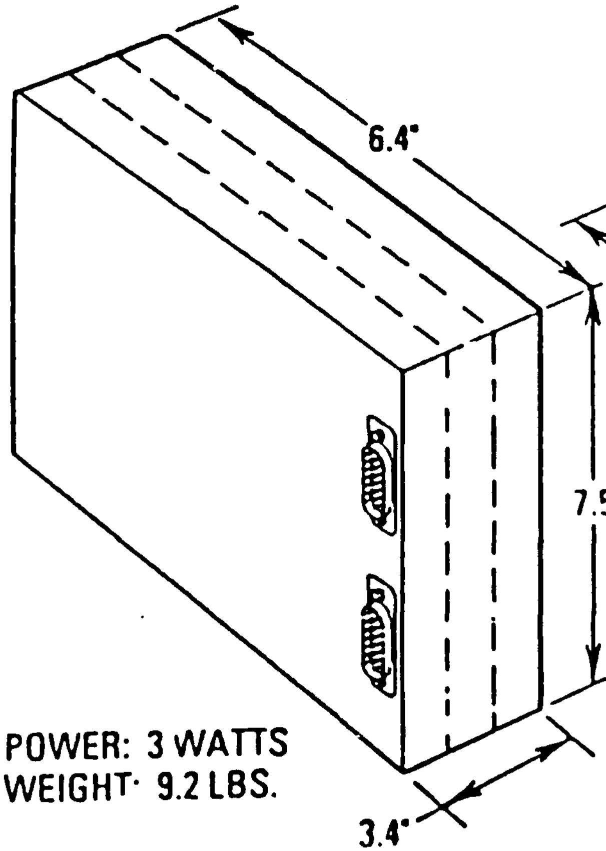
- Establish manufacturing guidelines for sensor/actuator active structures
- Understand sensor/actuator material behavior, structural placement, and interactions
- Miniaturize control electronics and decrease power demand
- Demonstrate space durability, performance, and operability

ACTEX Tripod



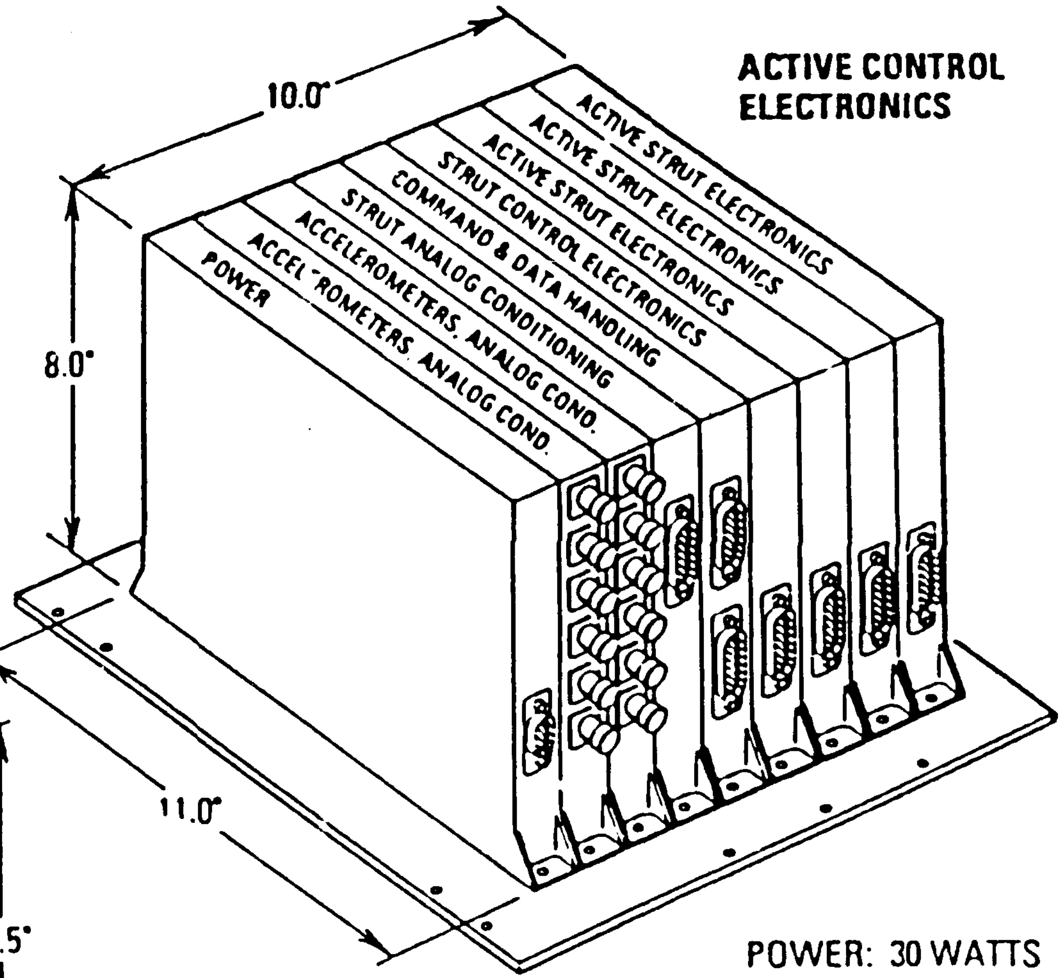
ACTEX Electronics

SOLID-STATE DATA RECORDER



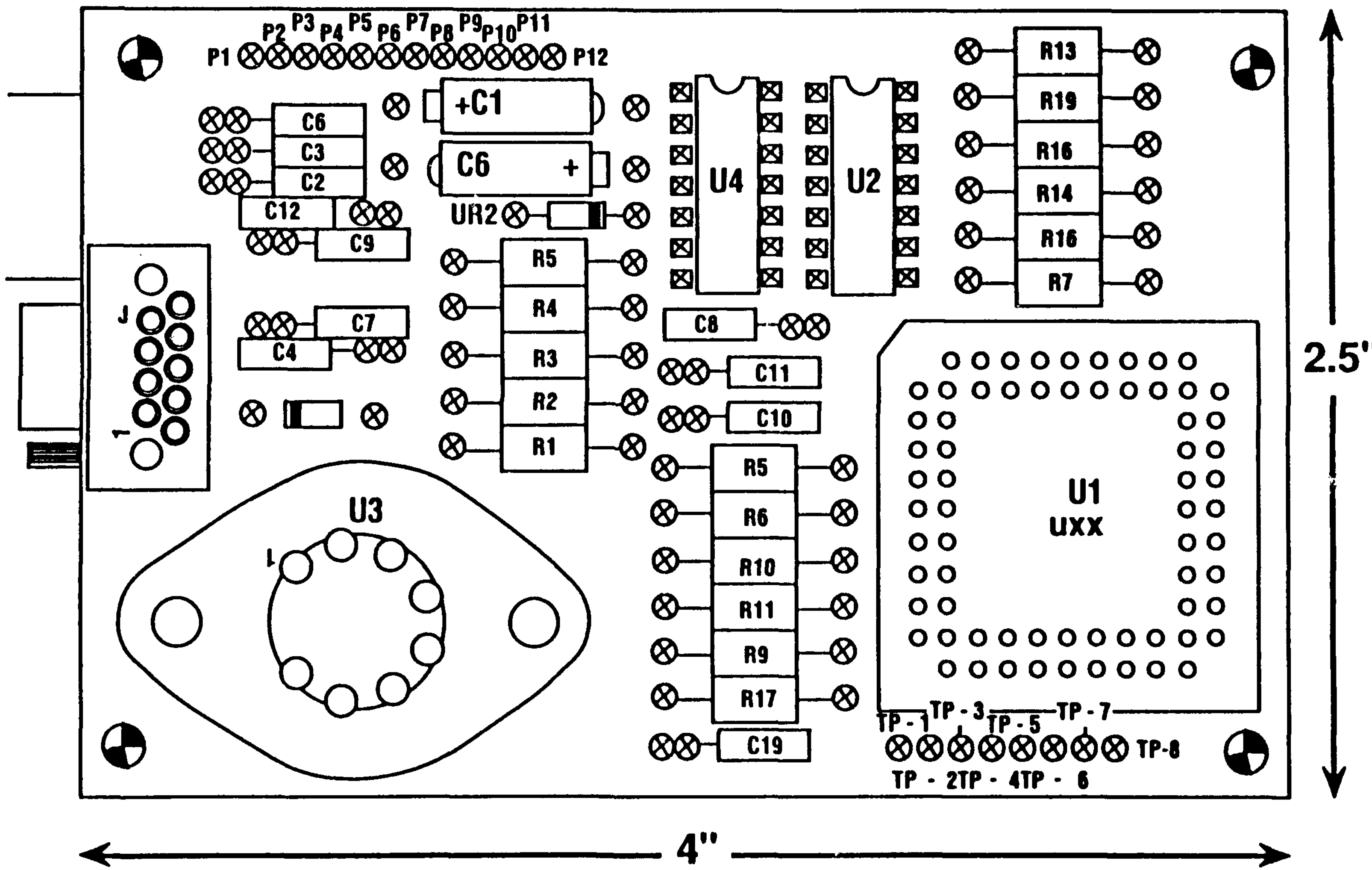
POWER: 3 WATTS
WEIGHT· 9.2 LBS.

ACTIVE CONTROL ELECTRONICS

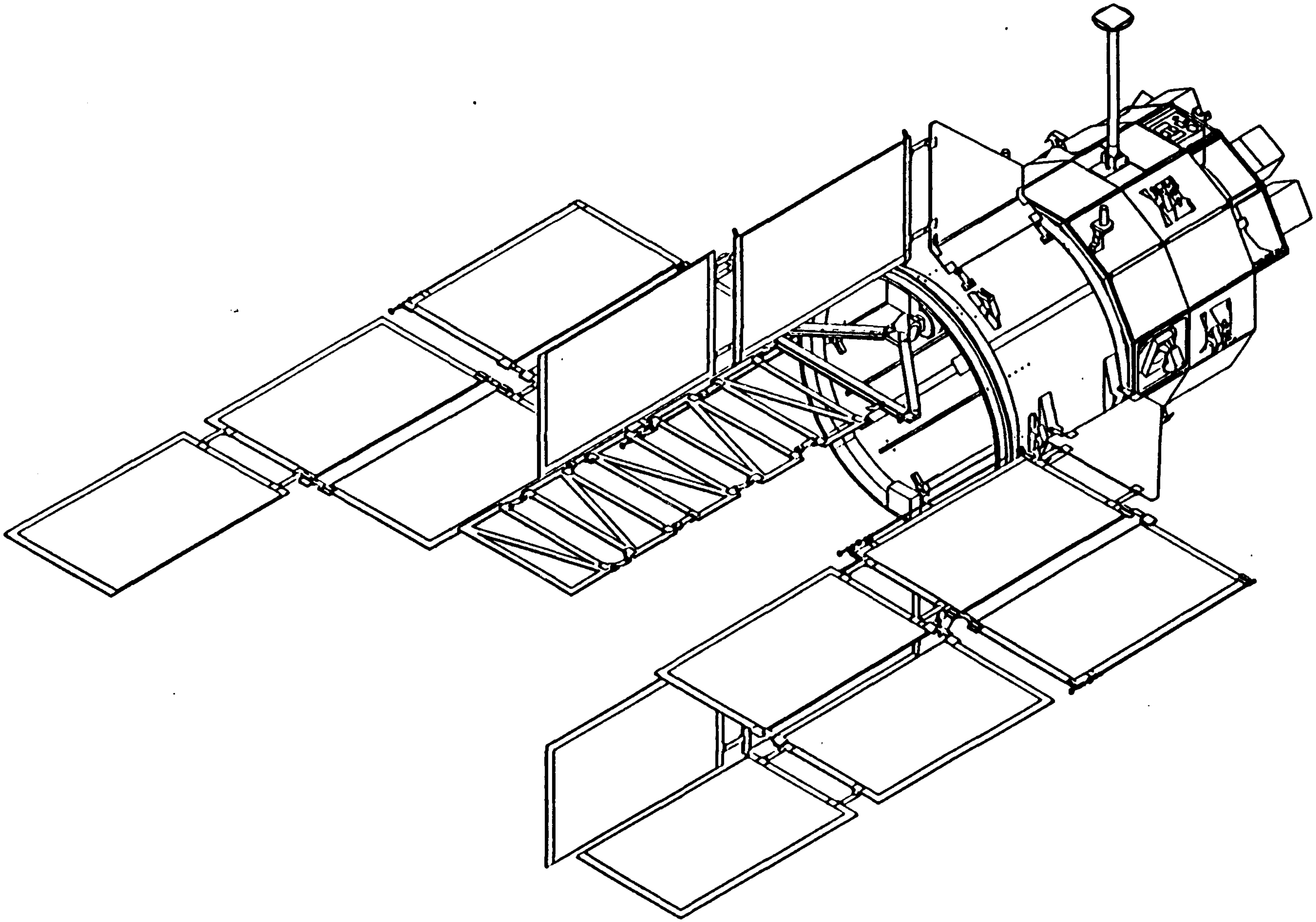


POWER: 30 WATTS
WEIGHT: 25 LBS.

AMASS Electronics Board Layout

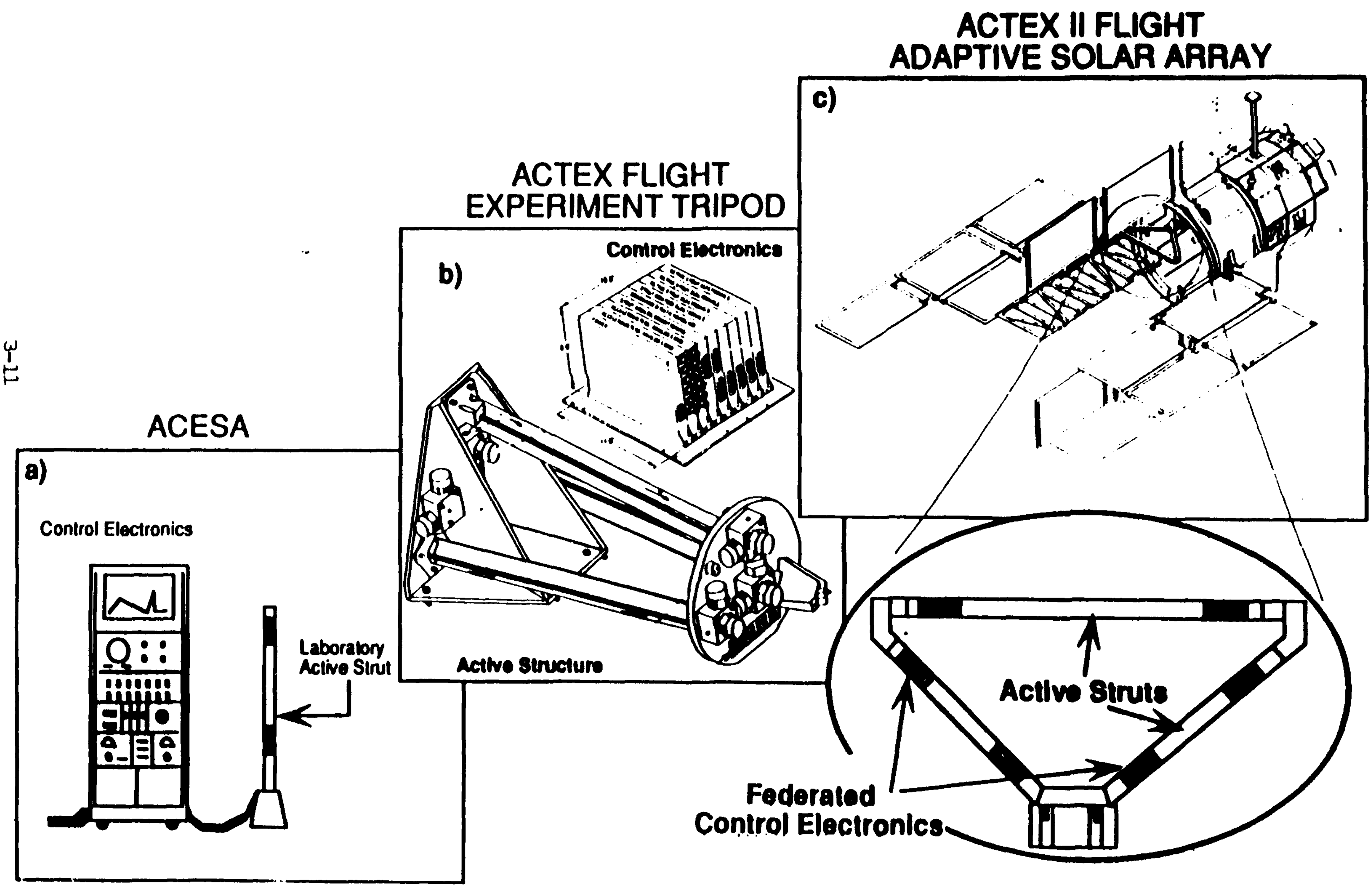


DEPLOYED SPACECRAFT CONFIGURATION



ADAPTIVE STRUCTURES TECHNOLOGY

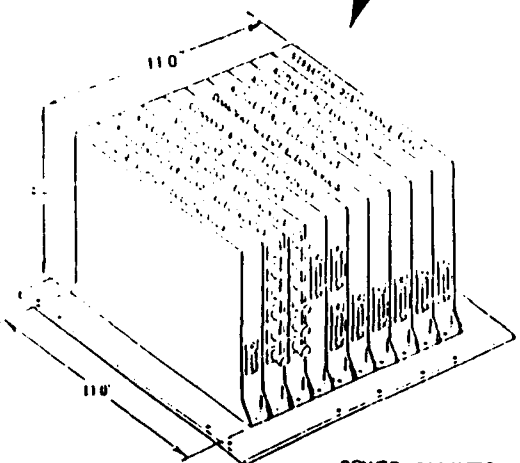
Miniaturization and Federation of Adaptive Structures Control Electronics Providing Power and Weight Reduction.



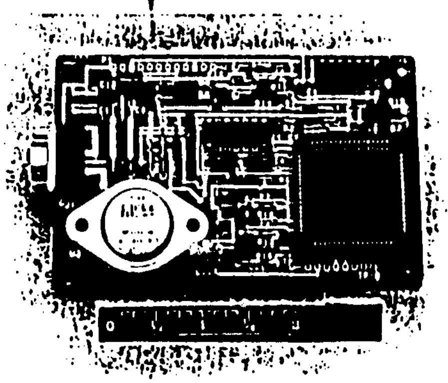
Maturity Path of Smart Structures Electronics

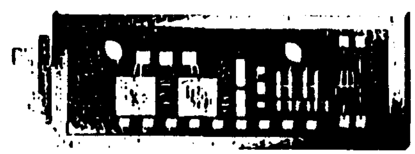
1991 — 1992 — 1993 — 1994 — 1995

	ACESA & ACTEX I	AMASS	ACTEX II	MCP
• Analog • Controlled by On/Off • Fixed Gains • Breadboard	• Digital Programmable Analog Compensator • Fixed Filters • Controlled by RS232 Interface • PC Board • 968 in^3 Volume • Remotely Located from Smart Structure	• Digital Compensator • Fixed Filters • Controlled by RS 232 Interface • PC Board • Automatic System ID • Local to Structure • 9.5 in^3 Volume	• Digital Compensator • Reprogramable Filters • High Speed Serial Interface • Multi Chip Module • Automatic System ID • Self Thermal Control • Over-Vibration Control • .95 in^3 Volume	• Digital Compensator • Reprogramable Filters • High Speed Serial Interface • Multi Chip Module • Automatic System ID • High Bandwidth • High Resolution • Over-Vibration Control • Reduced Interface Wire Count (local voltage control) • Inputs for Accelerometers and Force Transducers • .75 in^3 Volume



POWER: 30 WATTS
WEIGHT: 25 LBS.





On-Orbit Health and Environment Monitoring

Goal

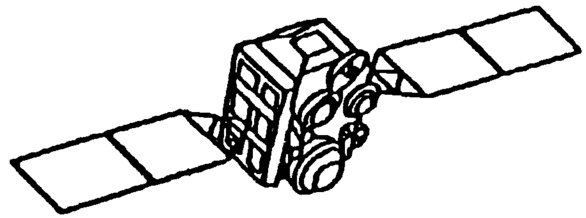
- Combine sensors, electronics, and structural materials into sensory structures for on-orbit monitoring within weight, surface area, and volume constraints
    - Monitor and report
        - Critical mechanism performance levels
        - Space environmental aging/damage effects
        - Threat attack warning/damage effects
    - Develop satellite subsystem multi-functional structures

Approach

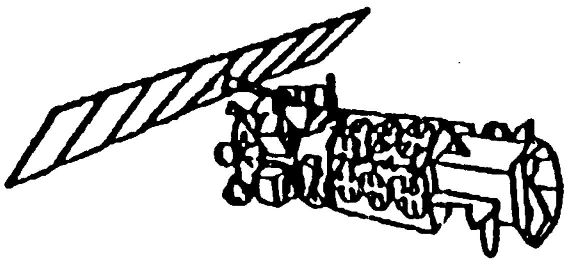
- Establish manufacturing guidelines for sensory structures
- Understand sensor, signal conditioning, and processing electronics interactions with structural materials
- Miniaturize electronics
- Identify signatures of various environmental/threat/damage effects
- Demonstrate space durability, performance, and operability

Tribomechanisms Applications/Problems

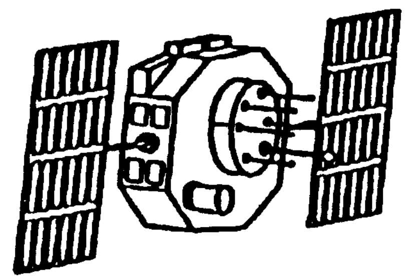
- Spacecraft critical moving mechanical assemblies



DSCS III
- *Slip Rings*
- Solar Array Drive
- *Reaction Wheel*



DMSP
- *Gimbal Bearings*
- Slip Rings
- *Momentum Wheel*
- Solar Array

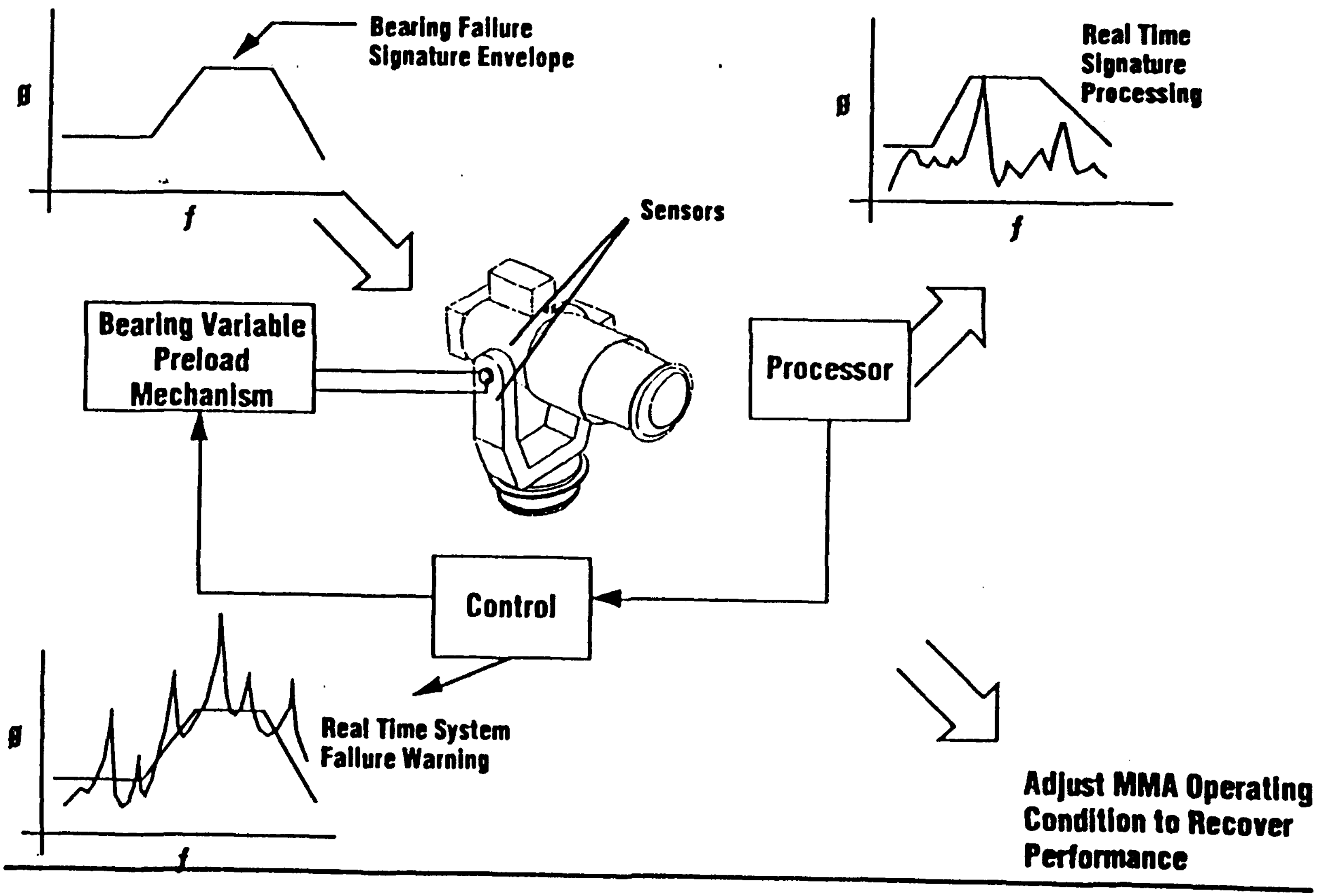


GPS
- *Reaction Wheels*
- Slip Rings
- Solar Array Drive

Italics indicate problems impacting mission performance

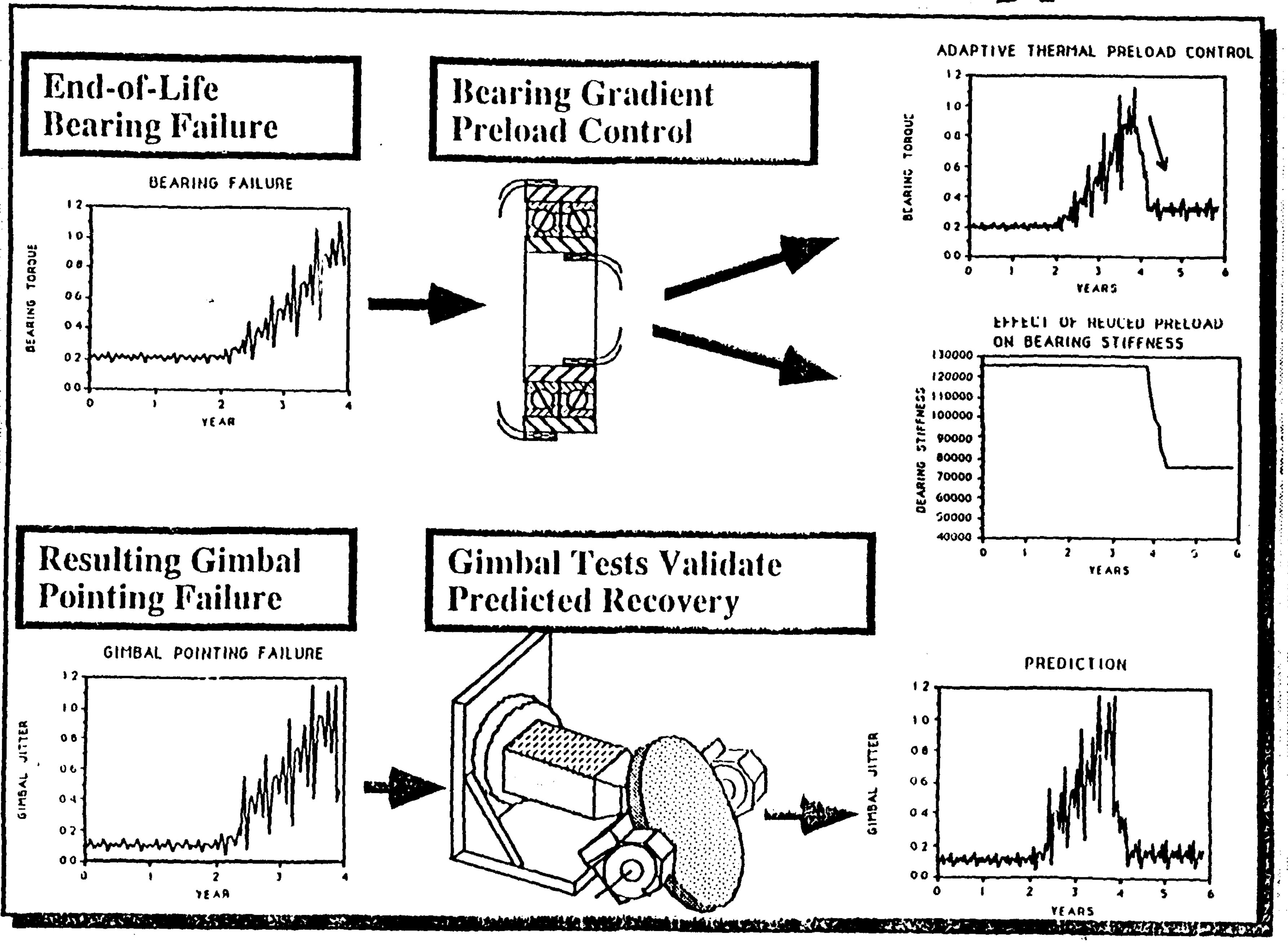
6-29-93-1M

Smart Tribomechanism

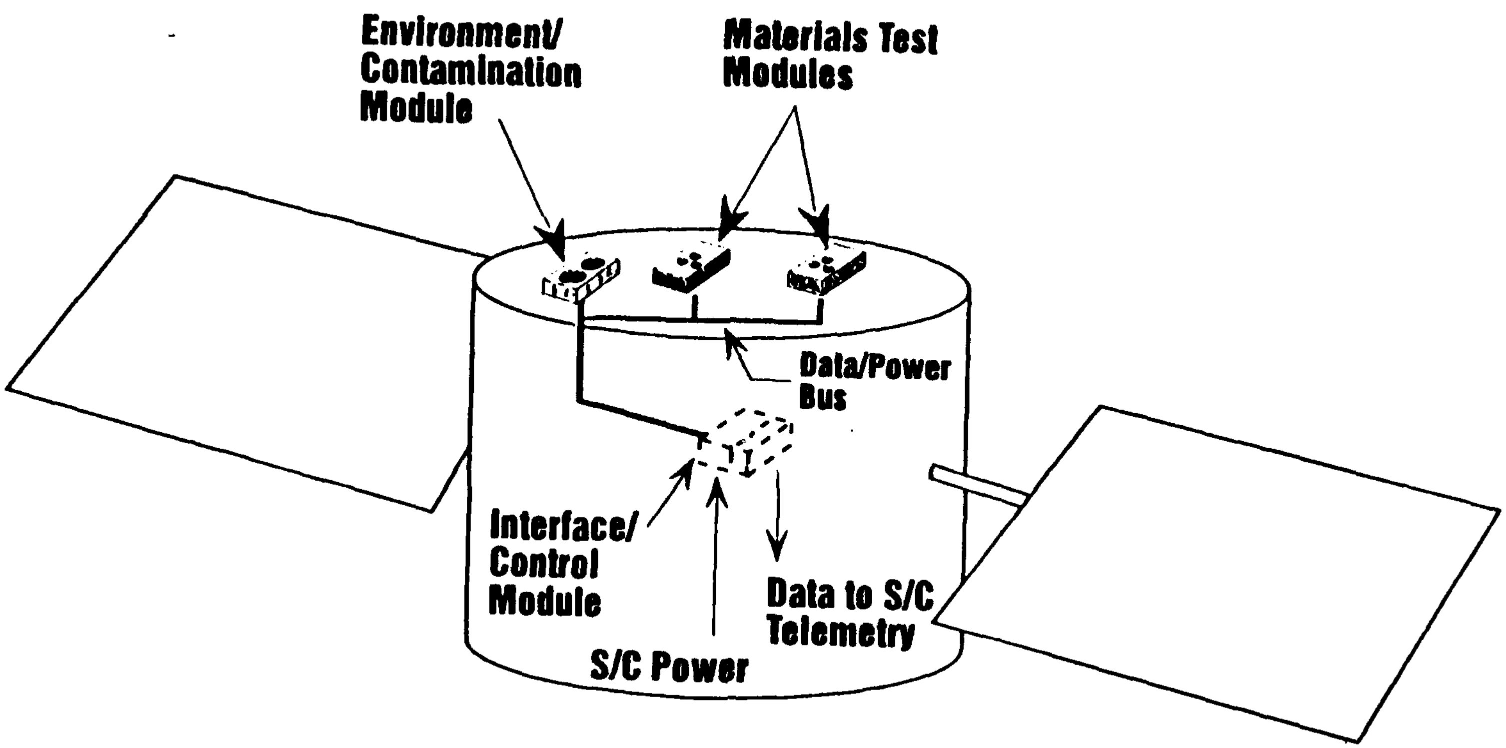


BEARING HEALTH MONITORING & ADAPTIVE CORRECTION

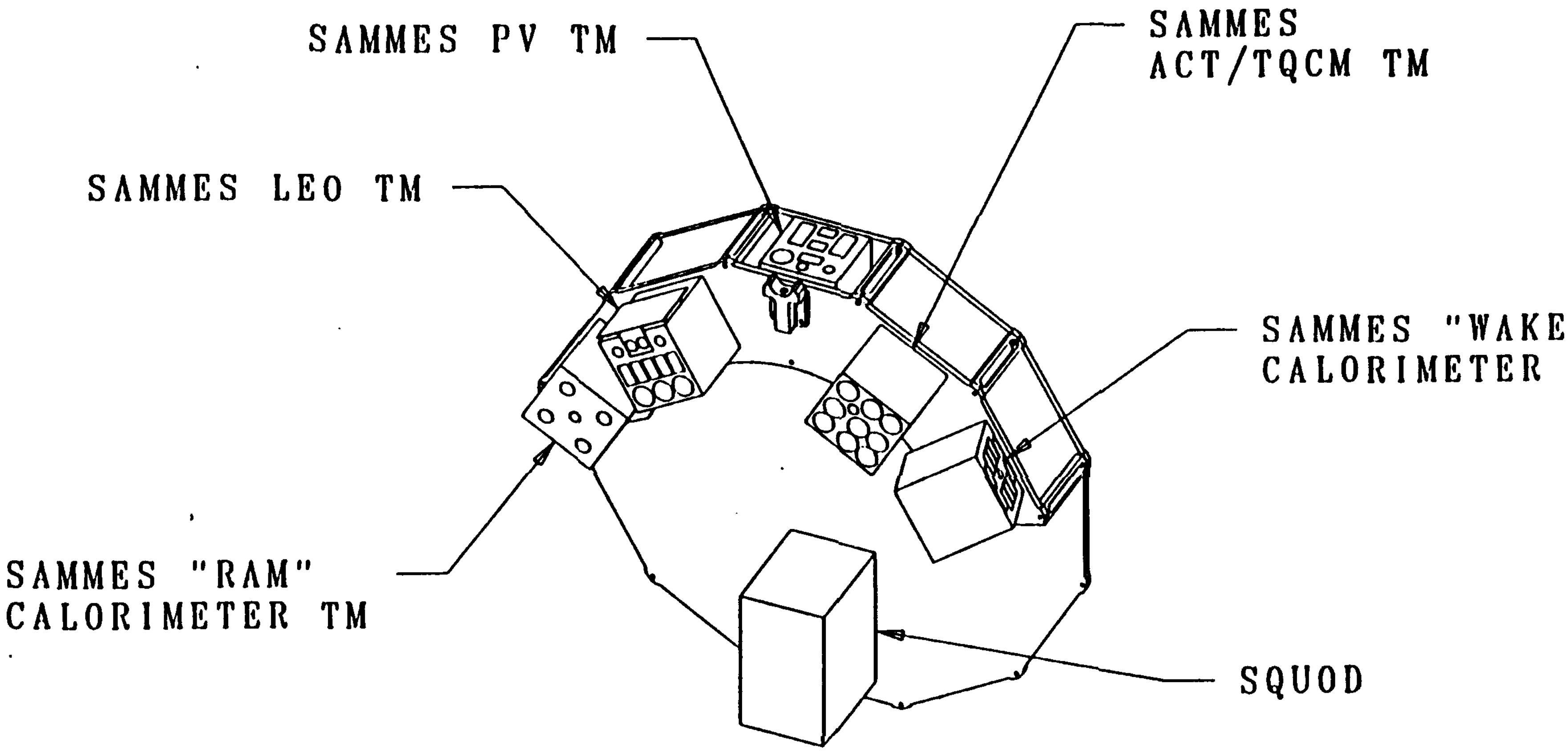
LOCKHEED TRIBOMATERIALS



Space Active Modular Materials Experiments (SAMMES) Concept

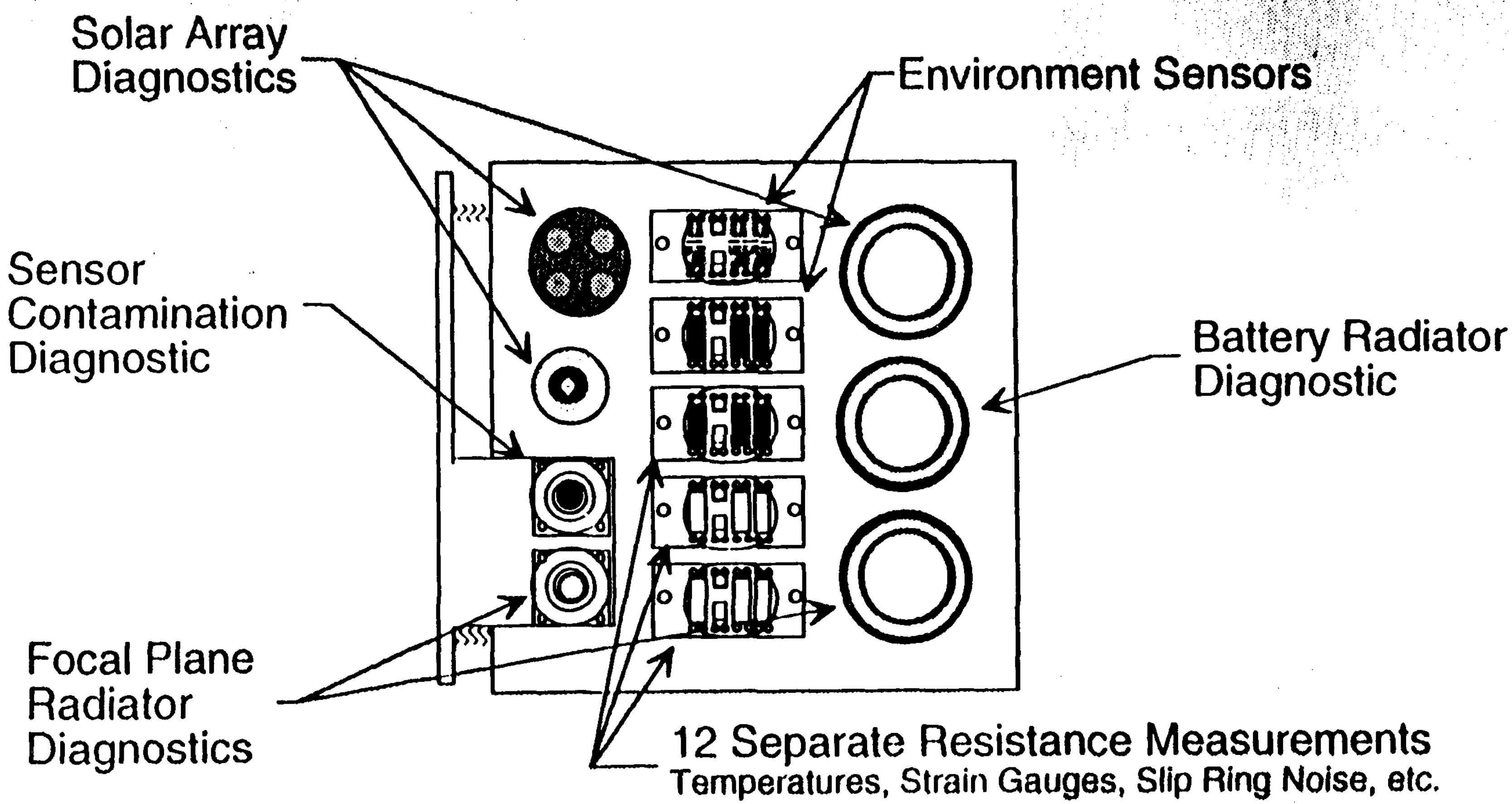


DEPLOYMENT MODULE LAYOUT



SAMMES LEO Module

Application as Satellite Health Monitor



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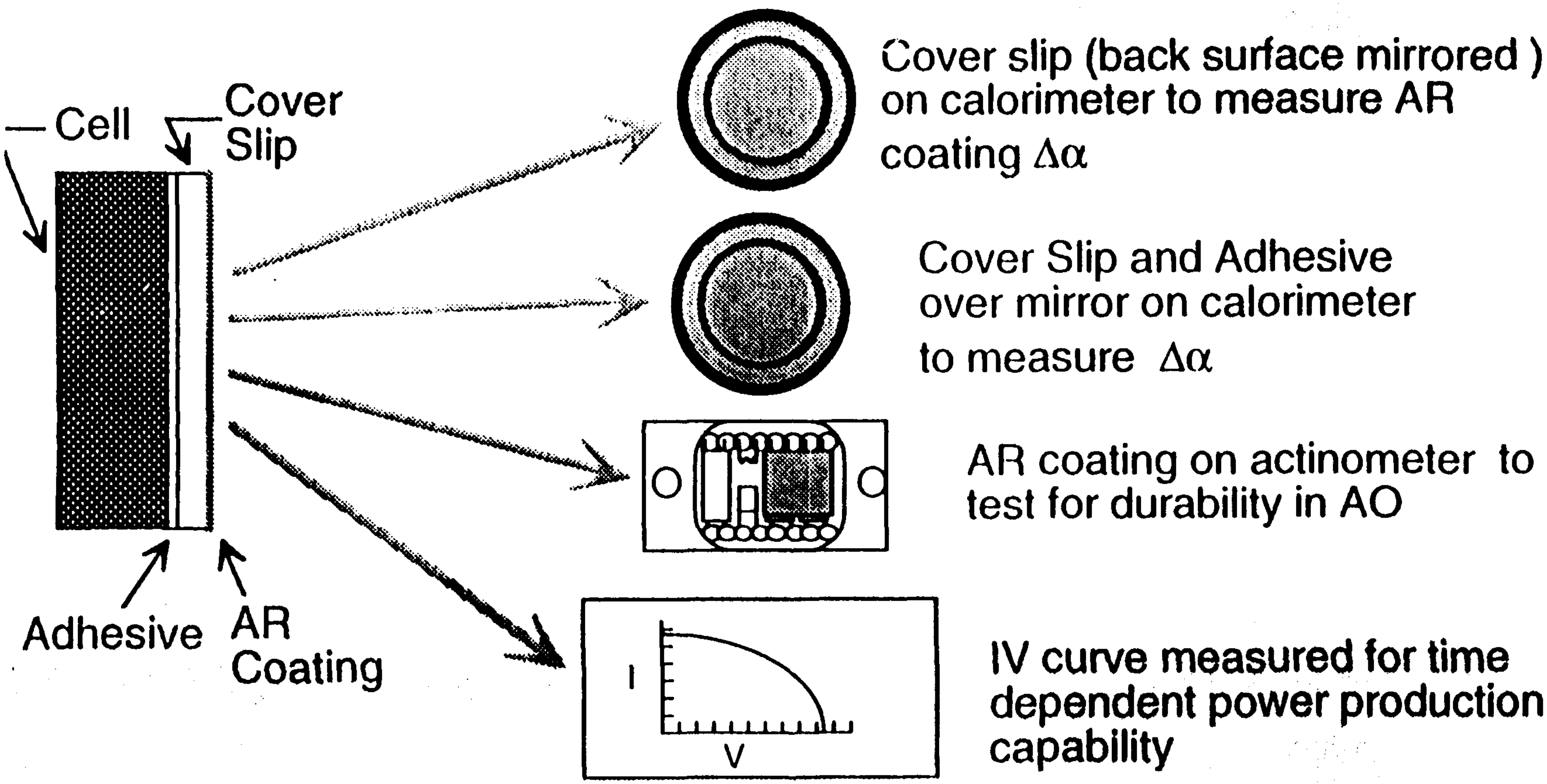
THE AEROSPACE CORPORATION

SAMMES Application Example

Advanced Solar Photovoltaic



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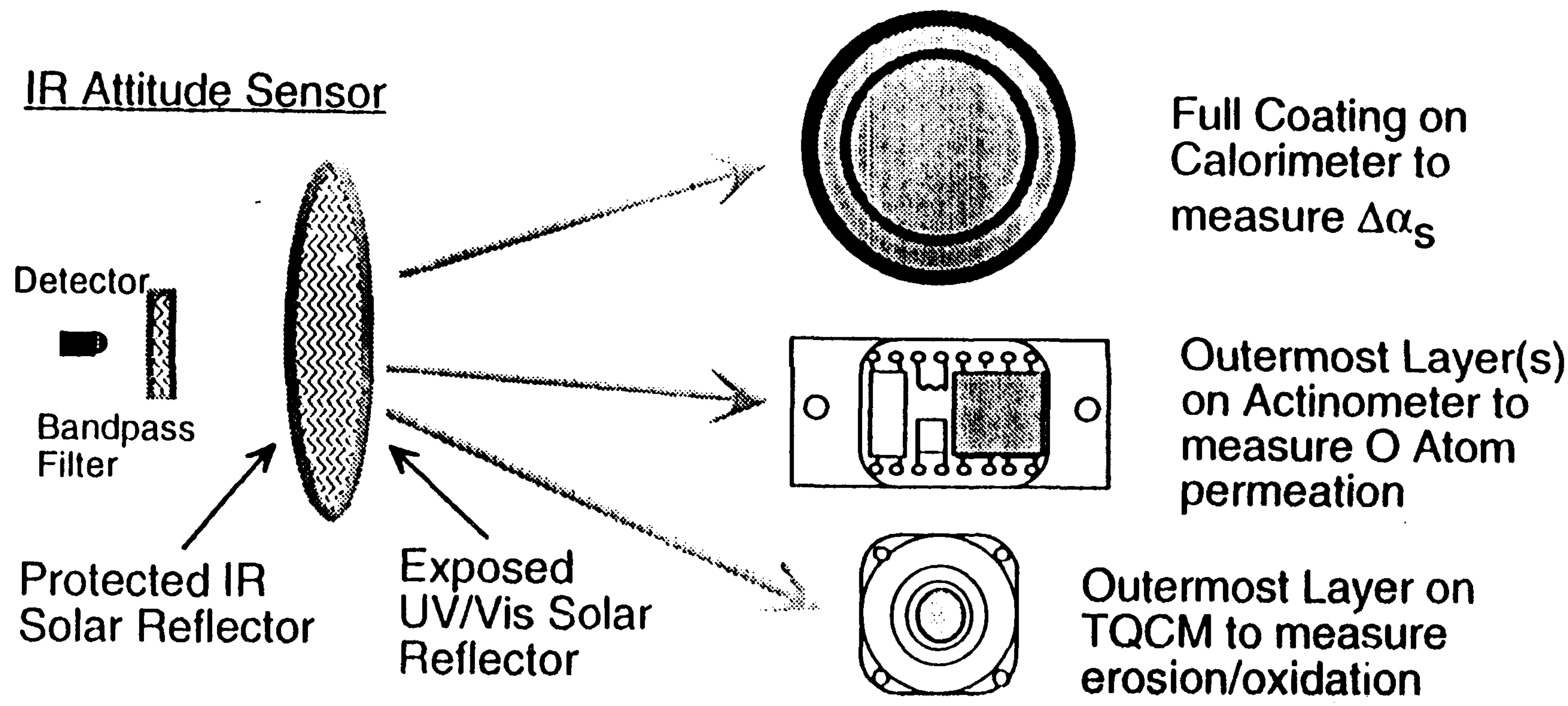
SAMMES Application Example

Multilayer Solar Rejection Coating



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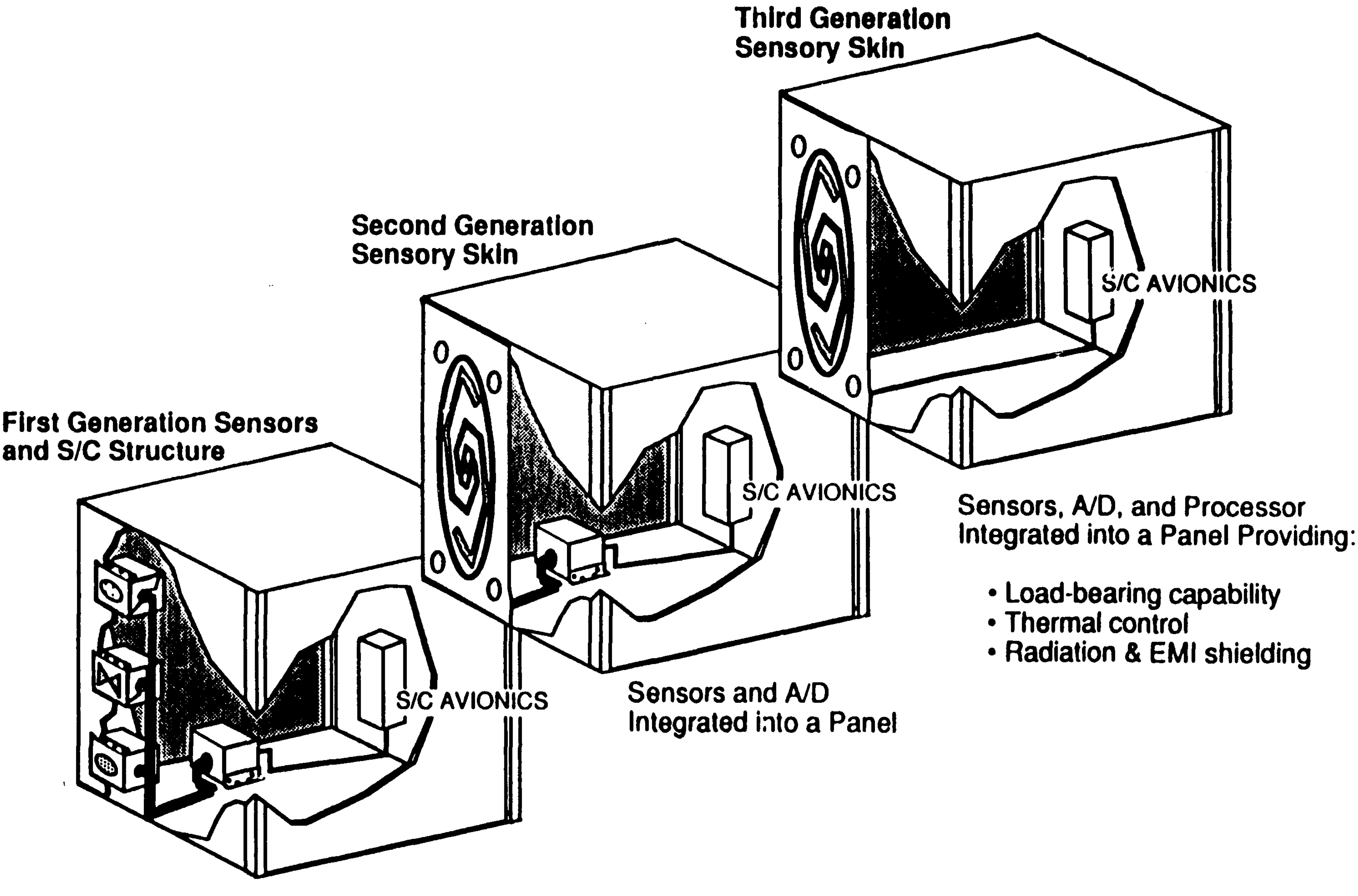
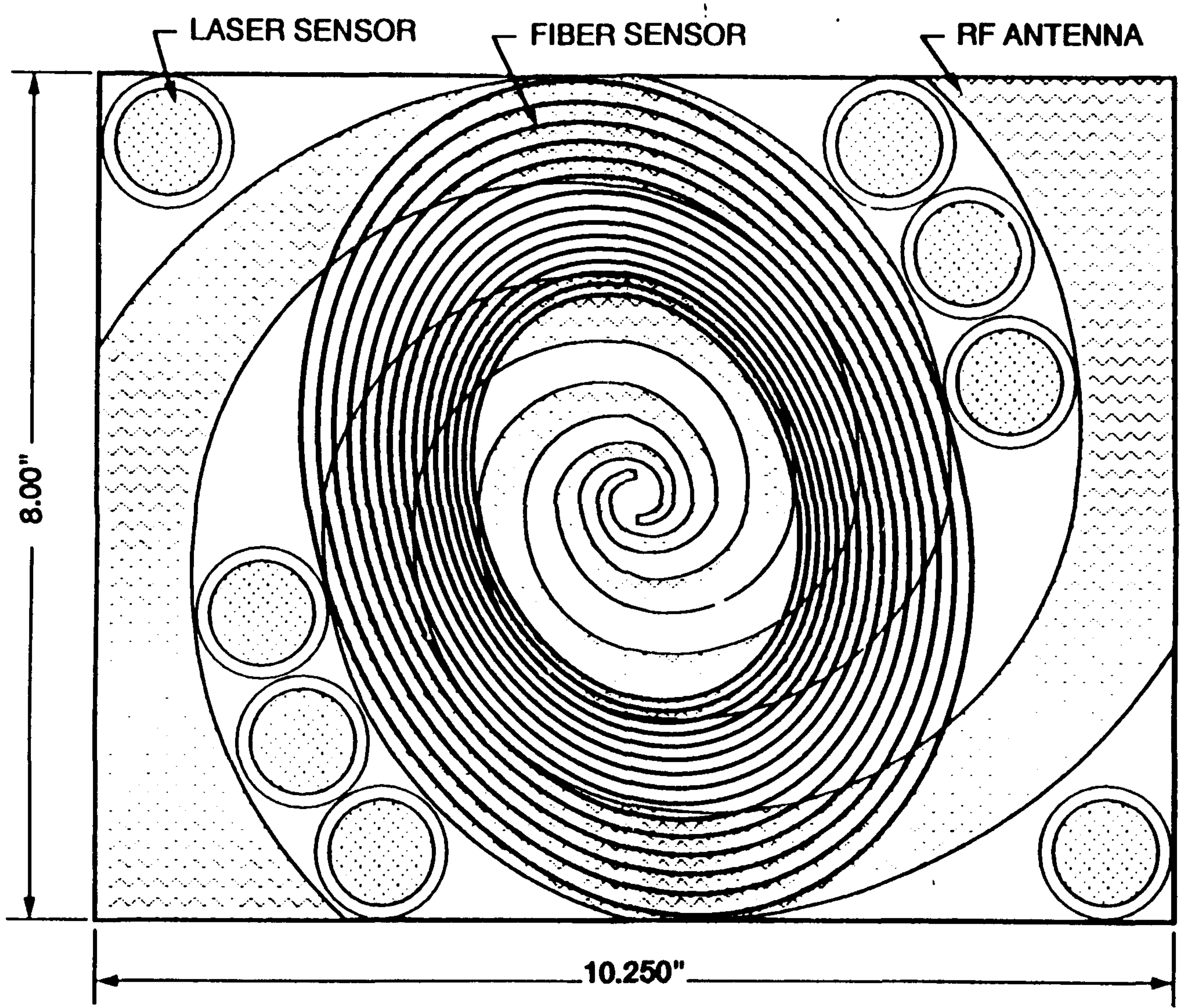
SENSORY STRUCTURES TECHNOLOGY

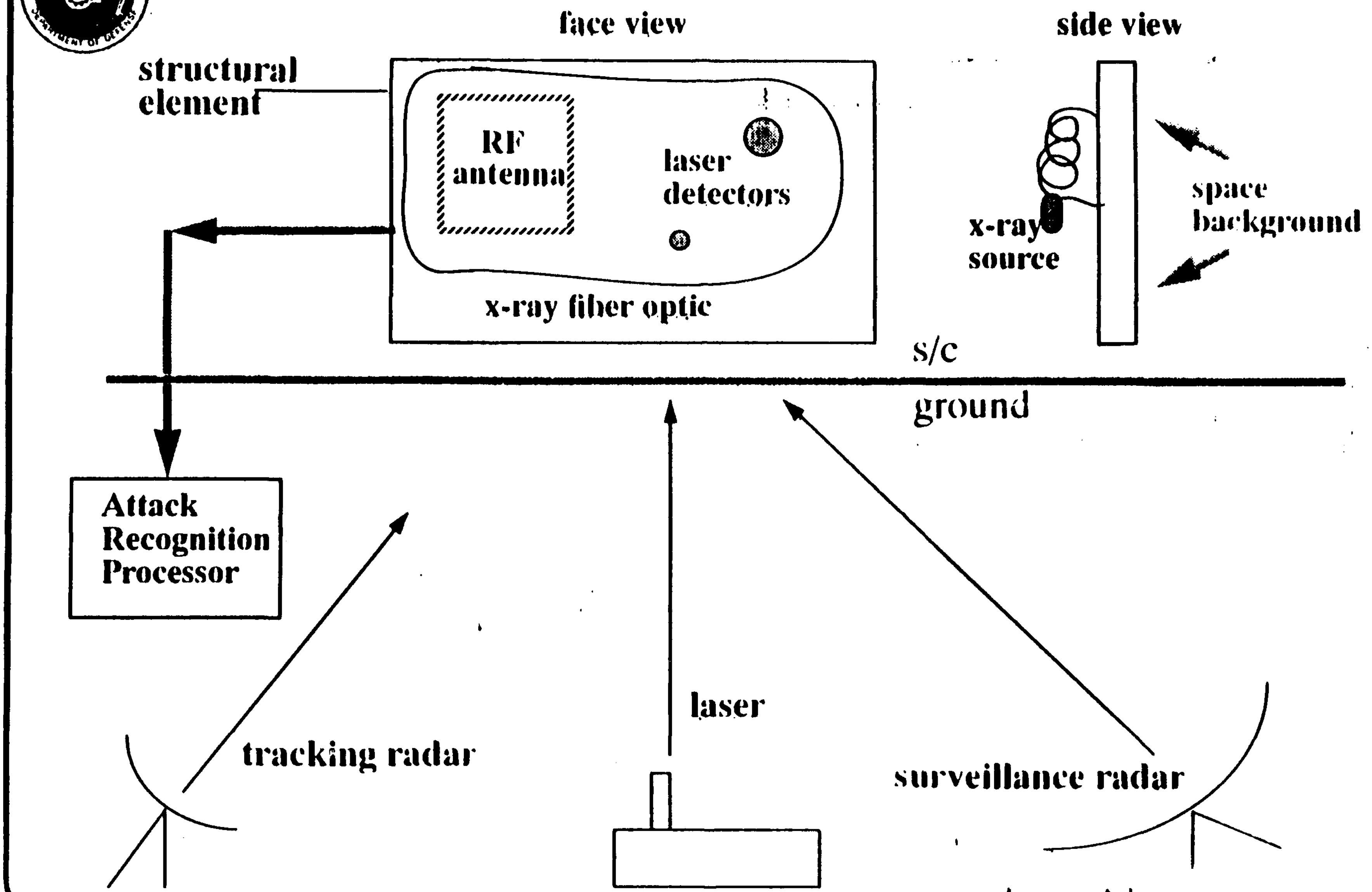


SAWAFE PANEL



Los Alamos

SAWAFE STEP 3 EXPERIMENT CONCEPT

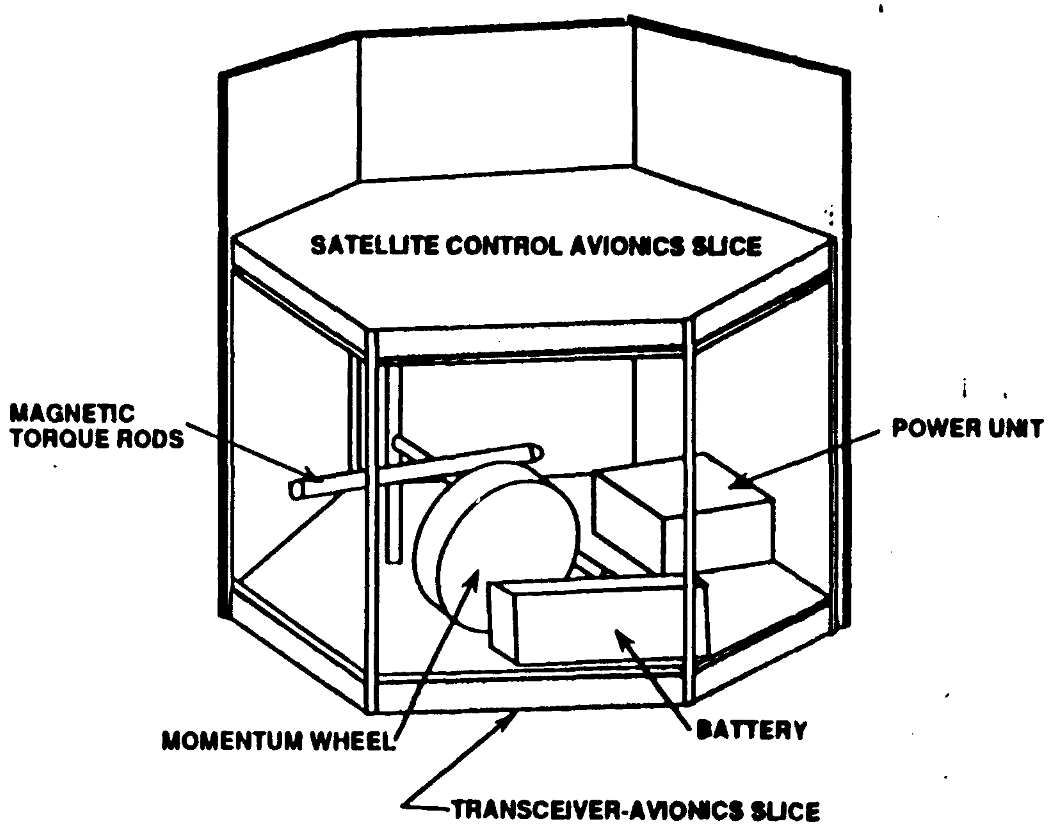


Los Alamos
Space Science & Technology

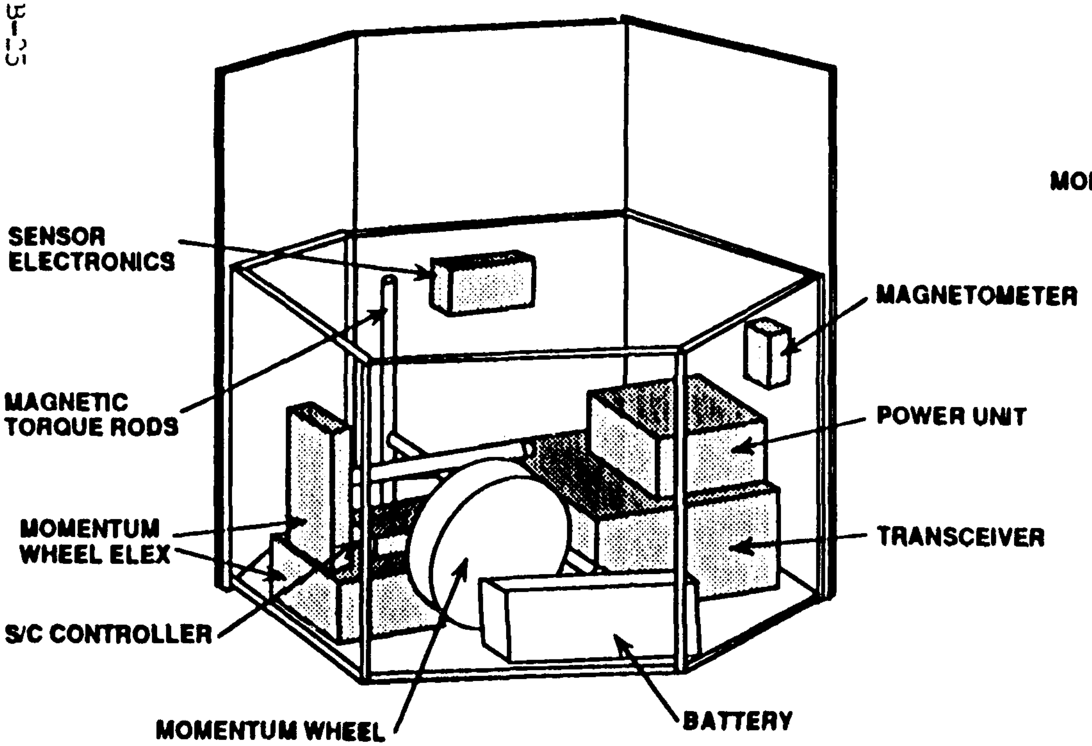
C-LINE #62013

MULTIFUNCTIONAL INTEGRATED STRUCTURES TECHNOLOGY

ENHANCED LOW WEIGHT BUS LAYOUT



TYPICAL SATELLITE BUS LAYOUT



Satellite avionics integrated to form multifunctional structural elements providing:

- Load-bearing capability
- Thermal control
- Radiation & EMI shielding

OBJECTIVES OF THE WORKSHOP

1. Identify Technical Issues for Spacecraft Sensory Structures

2. Assess the Viability of Initiating Research Efforts in Space Sensory Structures

3. Determine Steps in Technology Development: "What has to be done first?"

4. Suggest Near Term and Far Term Applications

JMS/dls:1
1/22/93

FACTORS FOR CONSIDERATION
(not in order of importance)

- Mechanics Issues of Embedded Electronics in Composite Structures
  - Stress, Strain, Electromagnetic Interaction, etc.
  - Existing Analytical Modeling Methods
- Spacecraft Qualification Requirements
- Spacecraft Assembly and Checkout Requirements, Ground Maintainability
- Fabrication, Producibility
- Expected Failure Mechanisms, Reliability
  - Space Environmental Effects
- Spacecraft Subsystems of Potential Interest
  - Communications, Attitude Determination and Control, Electrical Power, etc.
- Other

JMS/dls:2
1/22/93

APPENDIX C

DESIGN CONCEPTS

New Design Concepts

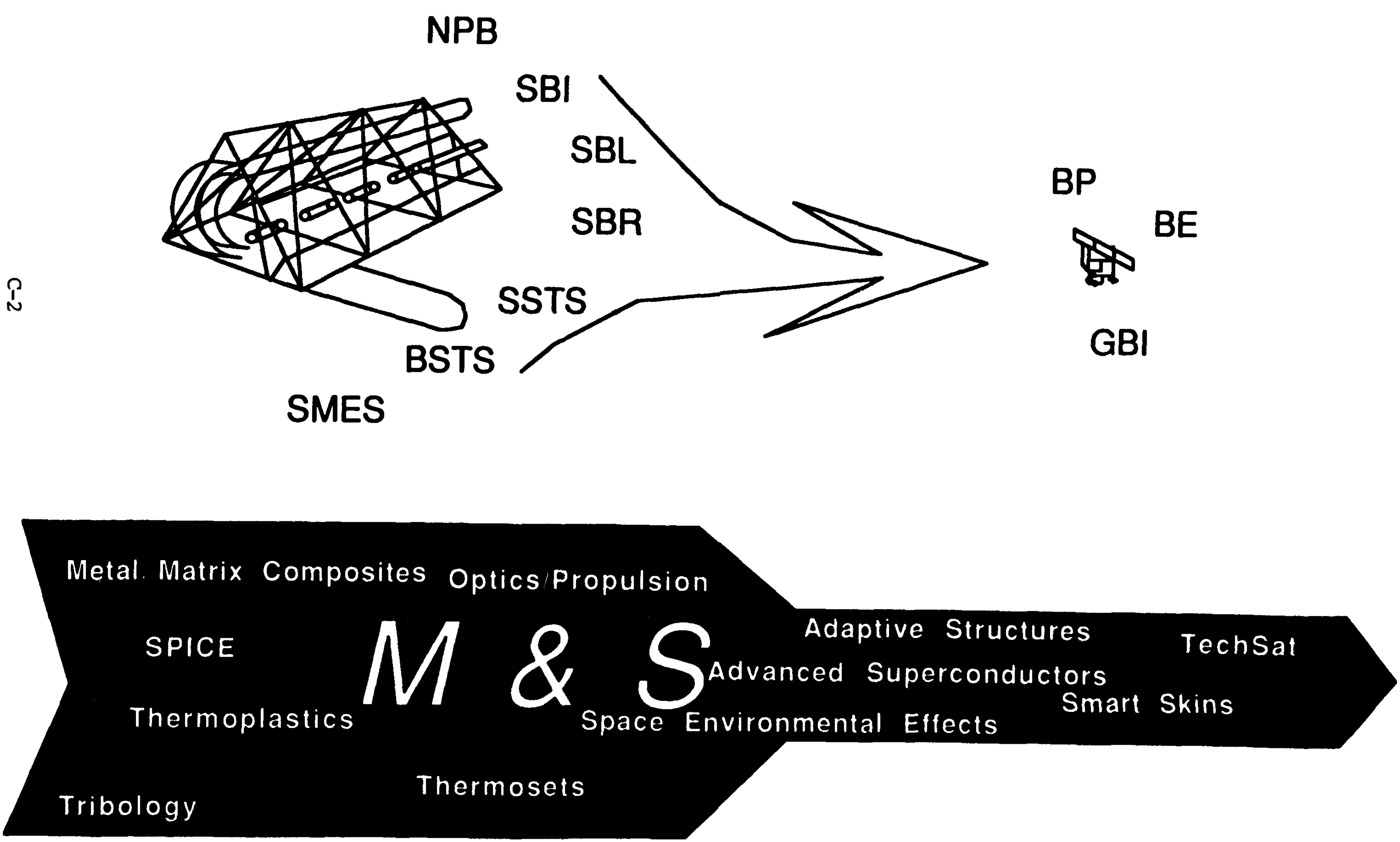
Workshop on Advanced Sensory Spacecraft Structures

February 10, 1993

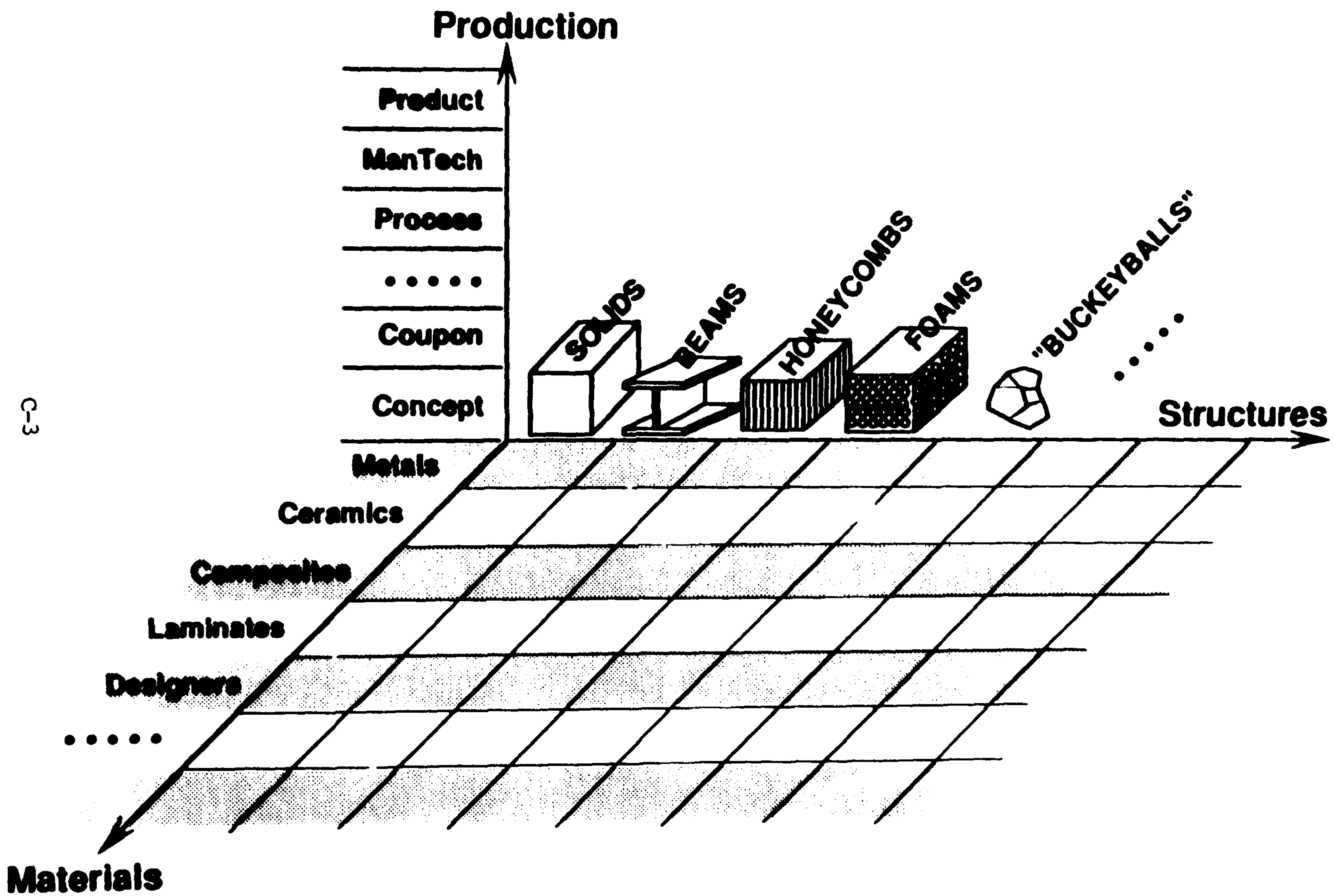
Chuck Byvik
WJSA

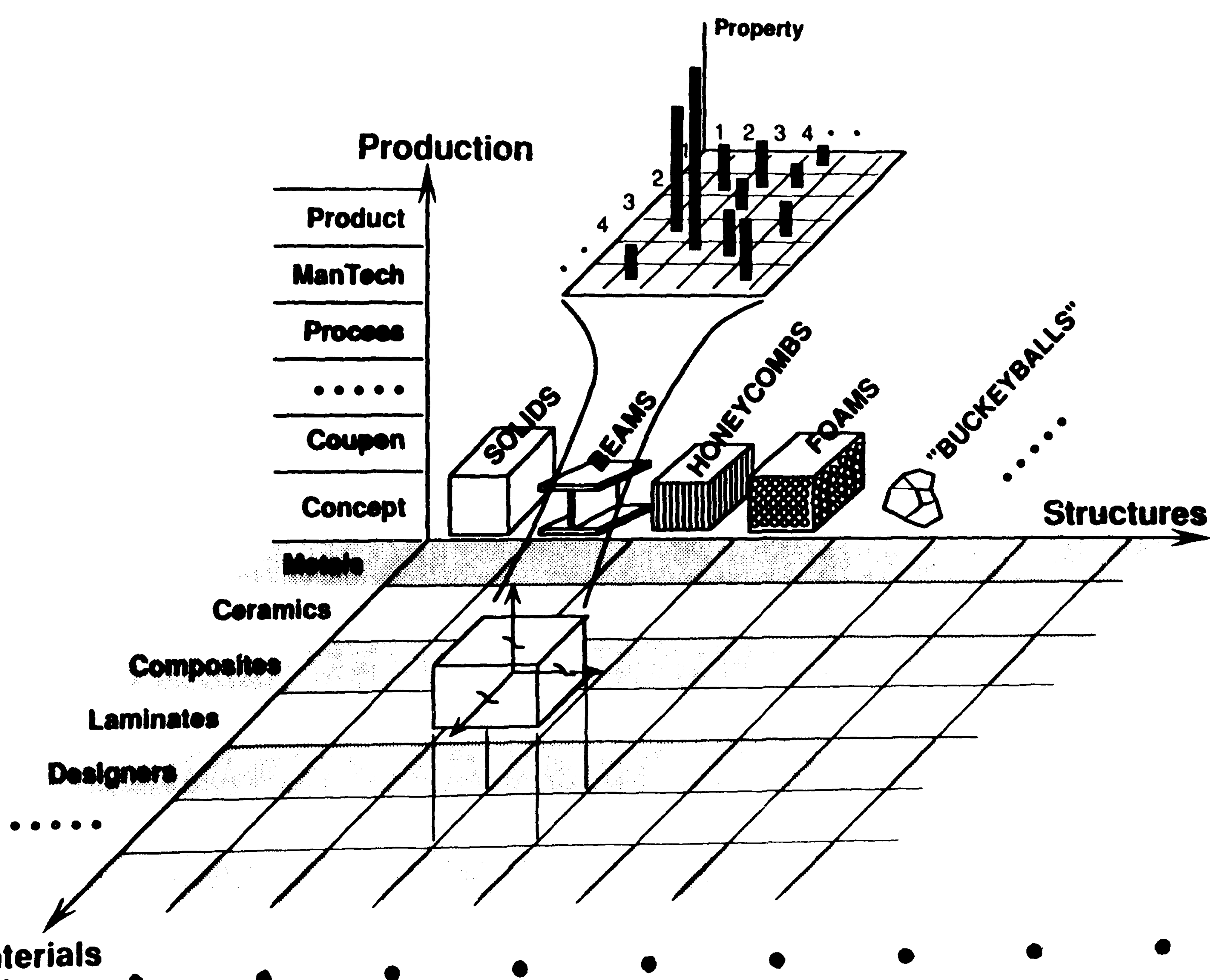
THE EVOLUTION OF SDIO and THE M&S PROGRAM

SDIO High ***"VOLUME"*** Requirements ⟶ SDIO High ***VALUE*** Requirements

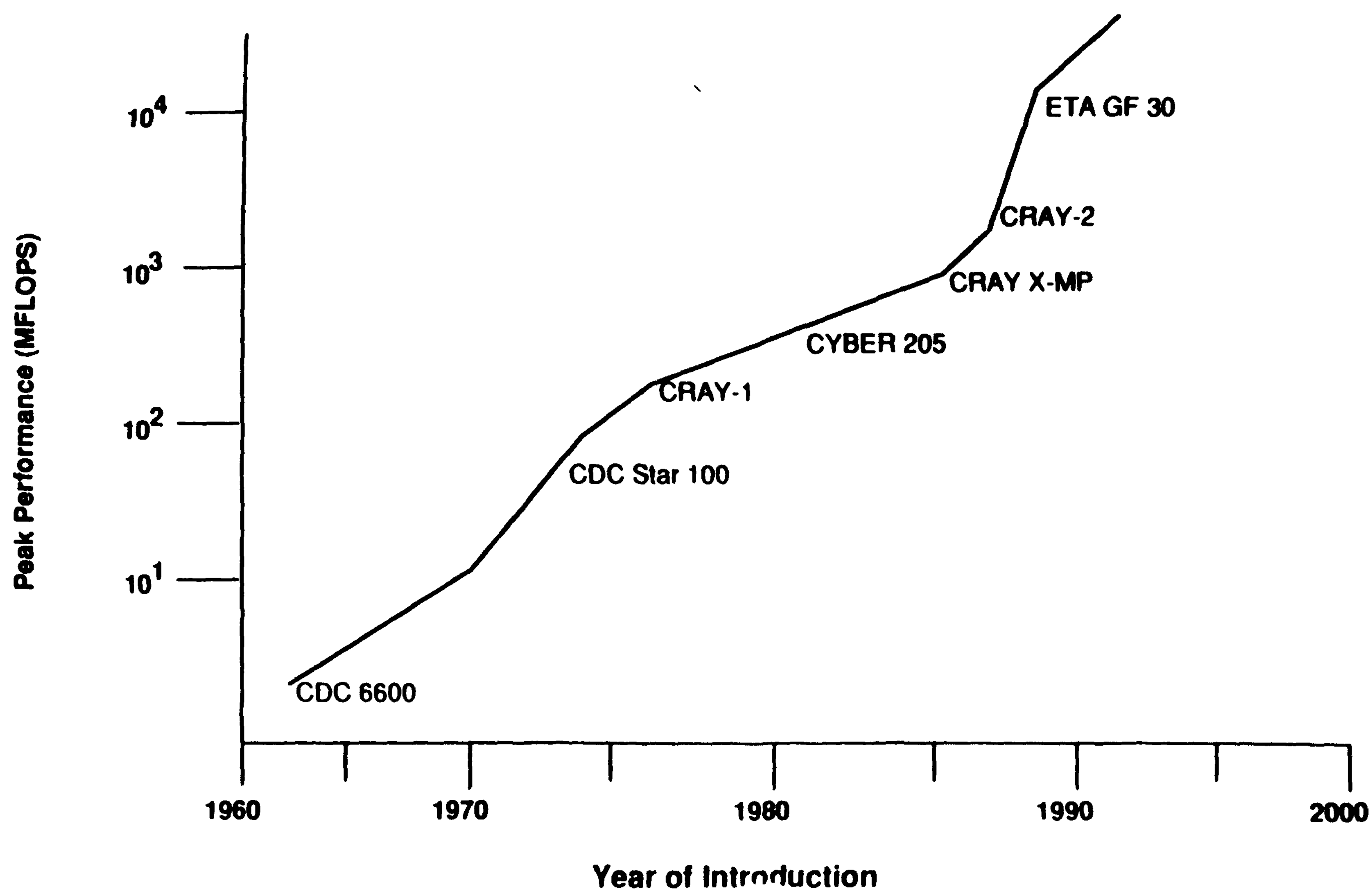


Materials and Structures--*A VIEW*




Property
1 2 3 4 . .
1 2 3 4 . .
Production
Product
ManTech
Process
• • • • •
Coupon
Concept
SOLIDS
BEAMS
HONEYCOMBS
FOAMS
"BUCKEYBALLS"
• • • • •
Structures
Metals
Ceramics
Composites
Laminates
Designers
• • • • •
Materials

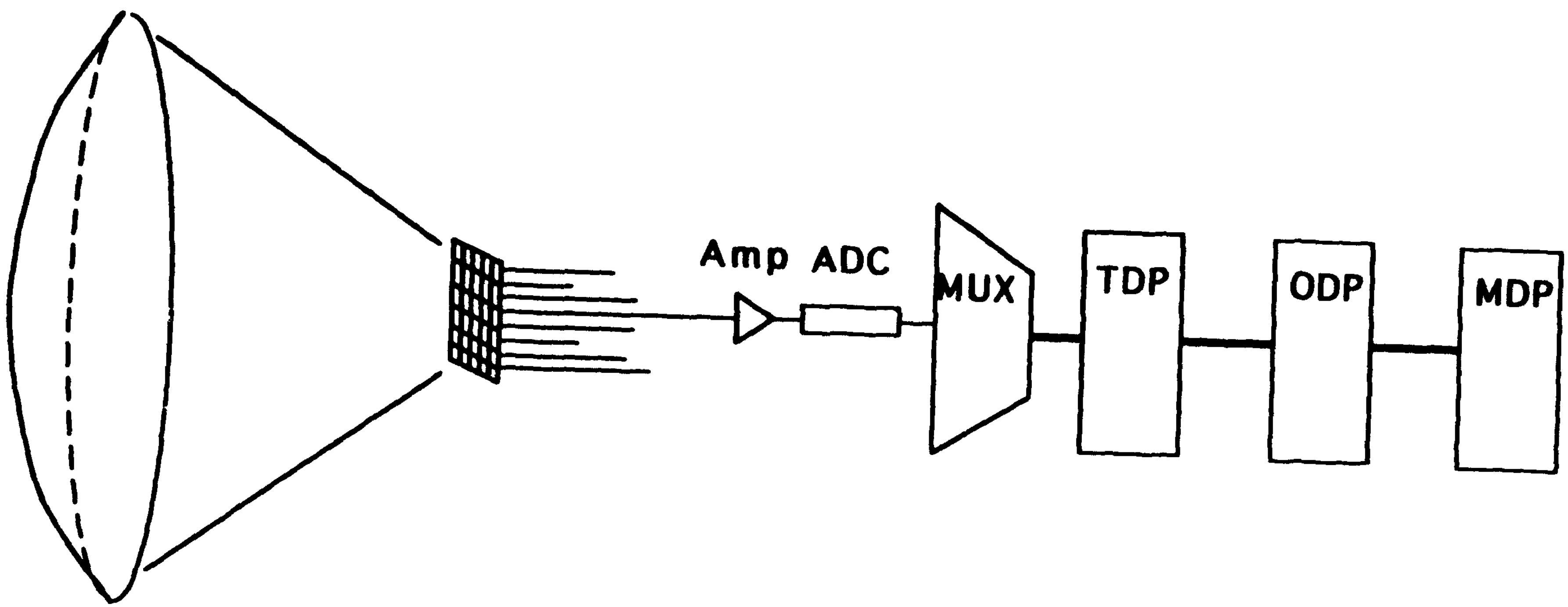
GROWTH OF COMPUTER SPEED



INTEGRATION OF ELECTRONICS AND FUNCTIONAL DISCIPLINES

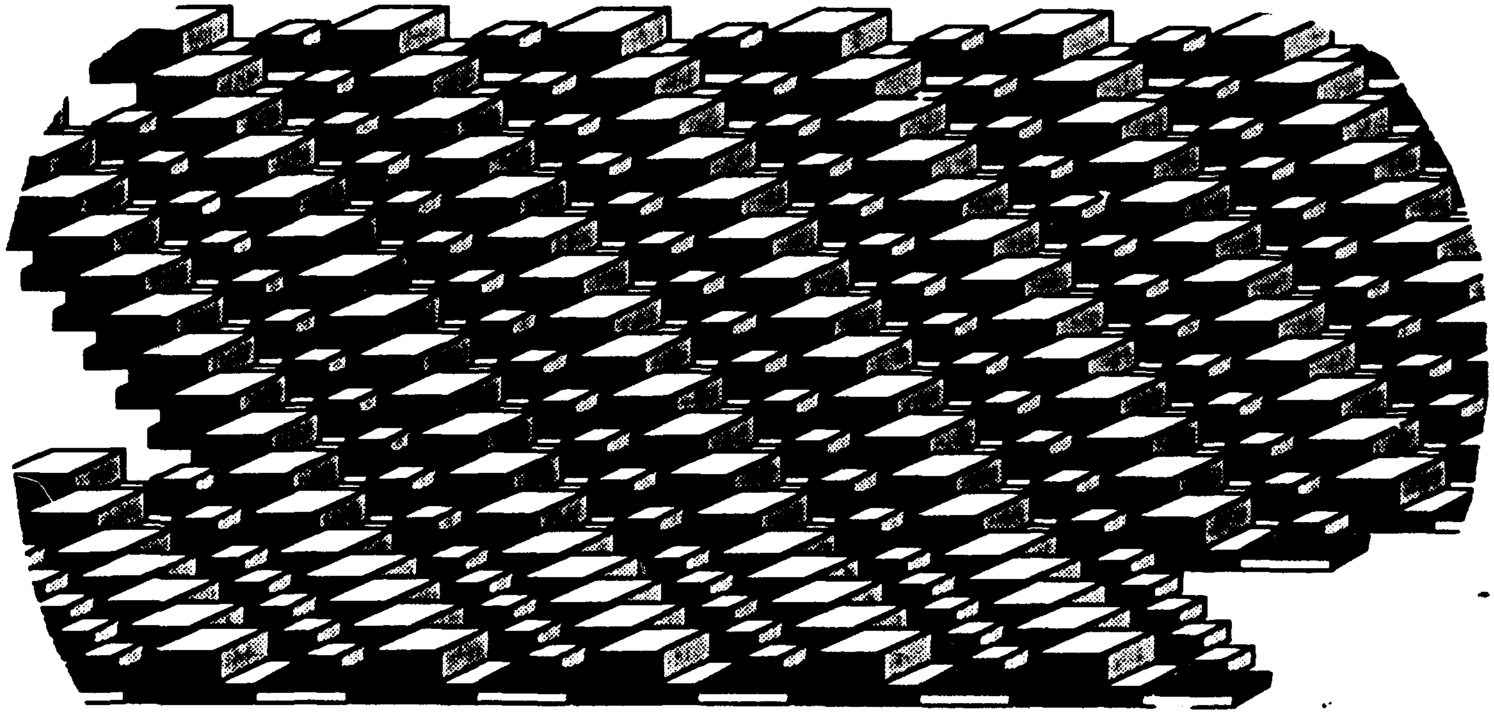
- Electronics with Structures → Adaptive Structures
- Electronics with Sensors → Sensory Structures
- Electronics with Optics → "Silicon Eyes"
- . . . → . . .

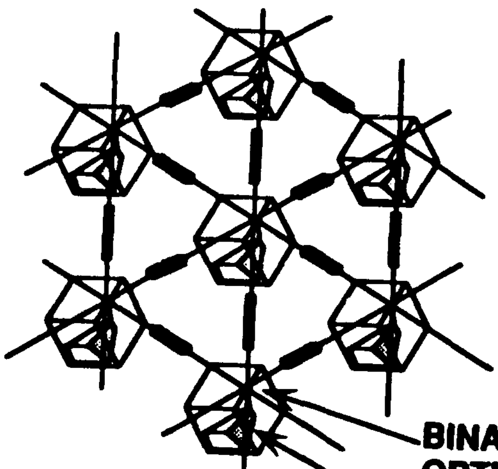
CLASSICAL OPTICAL SENSING SYSTEM



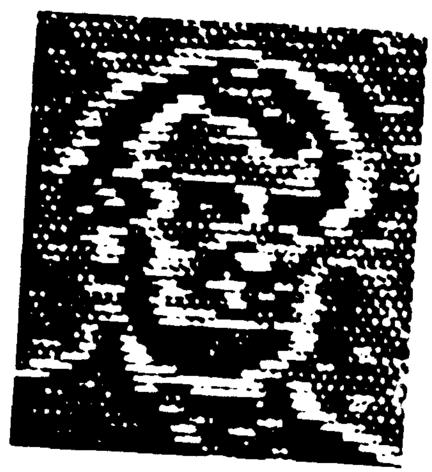
- Refractive or Reflective Optics
- Bit/Serial Data Stream
- Digital Signal Processing

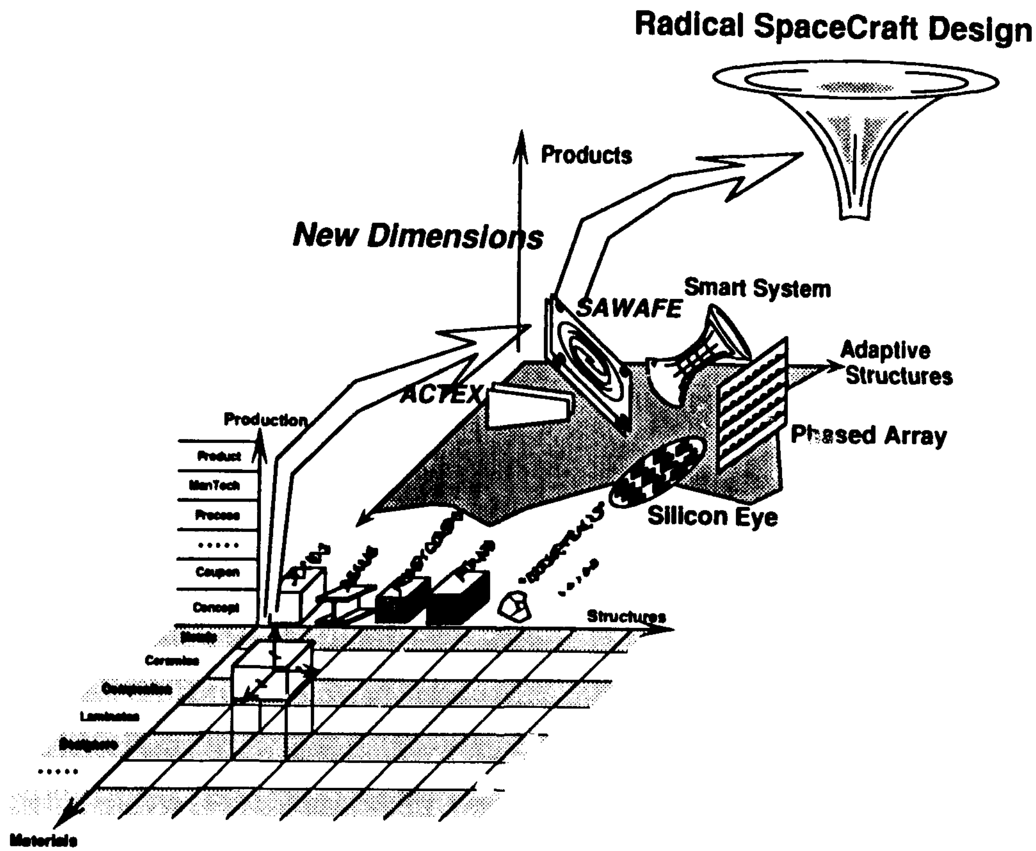
"SILICON EYE"



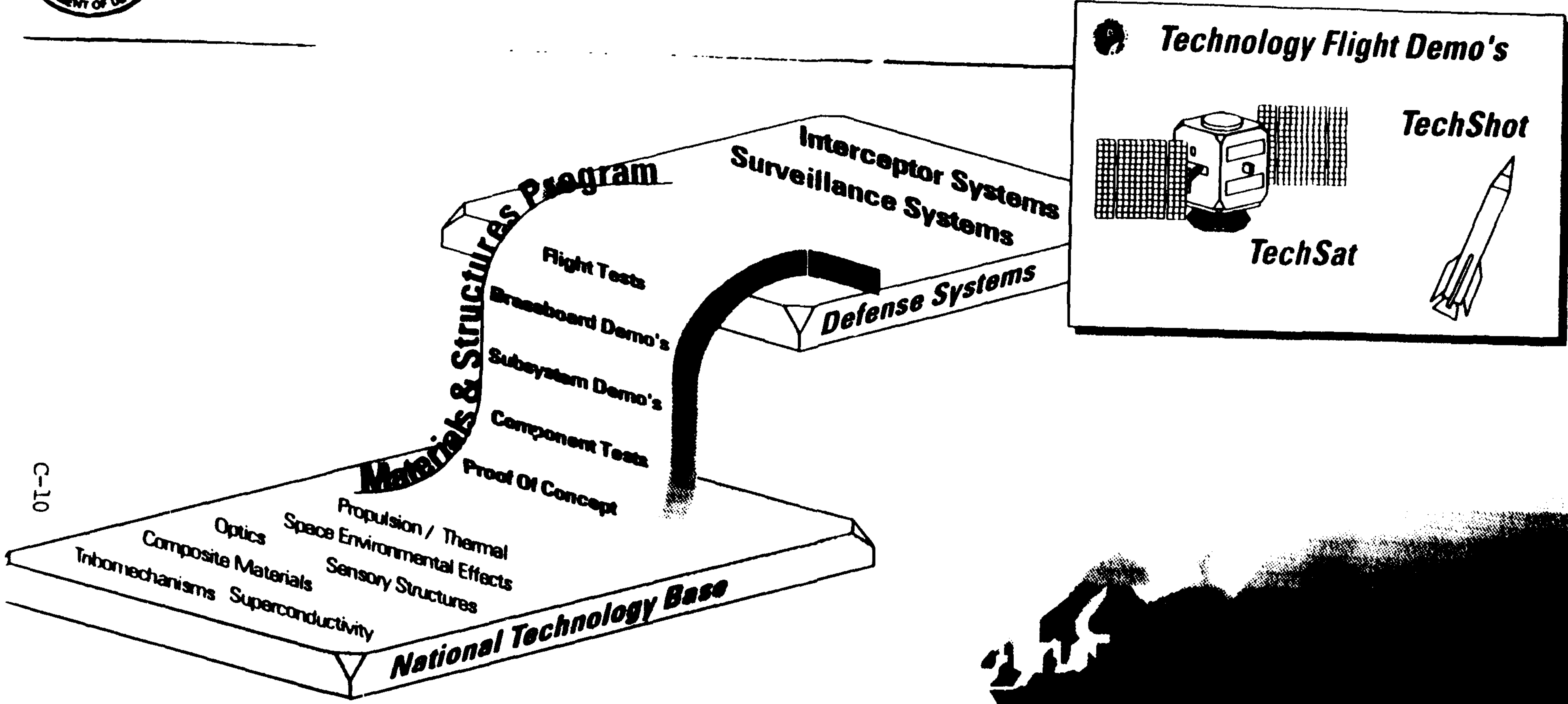


- Diffractive Optics
- Adaptive Electronics
- Analog Signal Processing



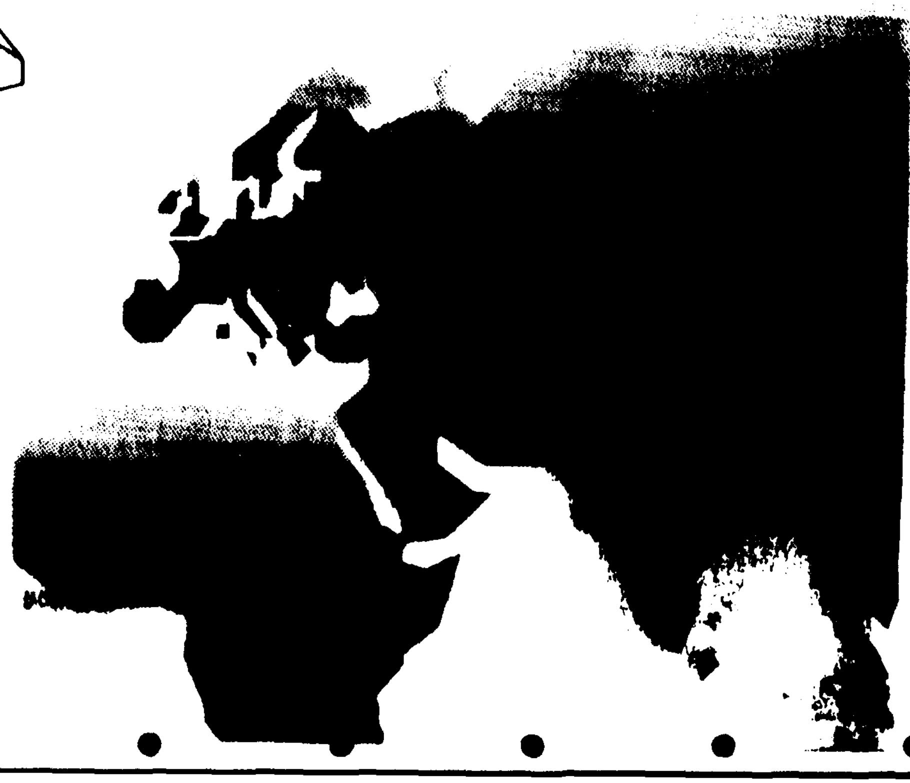

Radical SpaceCraft Design
Products
New Dimensions
SAWAFE
Smart System
Adaptive
Structures
ACTEX
Phased Array
Silicon Eye
Production
Product
ManTech
Process
Coupon
Concept
Structures
Ceramics
Materials

M&S Program Evolution



M & S Program Areas

- Adaptive Structures
- Space Evironmental Effects
- Lightweight Structural Materials
- Optical Materials
- Tribomechanisms
- Propulsion/Thermal
- Superconductivity



CONCLUSIONS

- *The Evolution to Small Satellites Requires*
  - ExoSkeletal Structural Designs - - *Fresh Approach to Satellite Design*
  - Integration of Satellite Functions - - *Interdisciplinary Collaborations*

- *"TechSat/TechShot" Programs Provide Low Cost/Risk Flight Heritage*
  - Focus Advanced Technology Development Efforts to System Requirements
  - Enhance Sensory Technology Insertion through "System Pull"

MULTI-FUNCTION STRUCTURES: USE IN
MINIMAL QUANTITY SPACECRAFT

INCORPORATION OF ELECTRONICS INTO STRUCTURAL ELEMENTS: IS IT WISE?

EXTREMELY WEIGHT CONSTRAINED VEHICLES

BENEFITS: ELIMINATES ONE MORE STRUCTURAL ELEMENT (AND THAT WEIGHT)

DIFICULTIES: THERMAL DISIPATION (SOLVABLE)

- EMI GROUND PLANES/SHIELDS DIFFICULT TO IMPLEMENT *(SOLVABLE WITH MONEY AND TIME)*
- SCHEDULE IMPACTS (SINCE STRUCTURE IS NOW AN ELECTRONIC COMPONENT, FABRICATION BECOMES MORE SERIAL)
- TEST AND INTEGRATION (REPAIR AND PROBLEM CORRECTION BECOMES MORE SERIAL)
- PRODUCIBLITY/COST WHENEVER LARGE, COMPLEX ELEMENTS ARE MANUFACTURED, UNLESS VOLUME IS HIGH, THE UNIT IS NOT COST EFFECTIVE

ASSEMBLY TECHNIQUES?

AVAILABLE ASSEMBLY TECHNIQUES GENERALLY SUITABLE FOR ADDING COMPONENTS TO THE STRUCTURE - IF IT WERE A REQUIREMENT

- CONDUCTOR DEPOSITION
- SURFACE MOUNT PARTS
- RADIATION RESISTANT PACKAGING

CONCLUSION

FOR VERY LOW VOLUME PRODUCTION (WHICH MIGHT INCLUDE LOW COST) SPACECRAFT OR NON WEIGHT CONSTRAINED APPLICATIONS IT IS NOT A GREAT IDEA TO COMBINE THE ELECTRONICS IN THE STRUCTURE.......

APPLICATIONS:

SOLAR ARRAYS
DEPOSITED INTERCONNECTS/REASONABLE THERMAL PERFORMANCE/ INCORPORATE ADAPTIVE STRUCTURE TO REMOVE MECHANICAL INTERACTIONS

ANTENNAS (CURRENT SMALL NRL STUDY)

ANTENNA ELECTRONIC FUNTIONS
INTEGRAL FRONT END ELECTRONICS AT THE FEED CAN BE BENEFICIAL

ANY FUNCTIONAL CONTROL OR TELEMETRY ELEMENT
COMPOSITE MATERIAL "JUST ANOTHER PRINTED CIRCUIT BOARD ELEMENT"

OPTICAL TRANSMISSION /PROCESSING MIXED MODE ELEMENTS
USE "MULTIWIRE" TECHNIQUES AND EMBEDDED FIBER OPTIC CABLE

CONCLUSION: ANY FLAT SURFACE AND A SUPPLY OF MONEY CAN BE MADE INTO A ELECTRONICS AND LOAD BEARING ELEMENT.

SOME CURRENT EXAMPLES

CPV STRUCTURE

COMPOSITE ELECTRONIC BOX

GENERAL QUESTIONS

DIELECTRIC CONSTANT (AND VARIATION OVER TEMPERATURE)
DIELECTRIC CONSTANT UNIFORMITY/TAILORING
THERMAL COEFFICIENT OF EXPANSION
COMPATIBLE WITH NON OUTGASSING ADHESIVES
MACHINABILITY
RADIATION IMMUNITY
PLATING TECHNIQUES
RESISTIVITY
COMPATIBLE WITH EXISTING FASTENERS (SCREWS/RIVETS ETC.)

Workshop on Advanced Sensory Spacecraft Structures

PROGRAM REQUIREMENTS & TECHNOLOGY INFUSION

10 February 1993

A. S. Bicos / D. L. Edberg
MCDONNELL DOUGLAS AEROSPACE
HUNTINGTON BEACH, CALIFORNIA

OUTLINE

- TECHNOLOGY NEEDS
- PROGRAM NEEDS
- TECHNOLOGY INSERTION
- EXAMPLE

PROGRAM NEEDS

MCDONNELL DOUGLAS

SYSTEM DEMONSTRATION PROGRAMS

- MAXIMUM BENEFIT/RISK RATIO
- MISSION ENABLING FUNCTION
- MISSION ENHANCING FUNCTION
- MINIMIZED IMPACT ON OTHER SUBSYSTEMS
- TIMELY TECHNOLOGY DEVELOPMENT

TECHNOLOGY NEEDS

TECHNOLOGY DEVELOPMENT

- BASIC & APPLIED RESEARCH (6.1, 6.2)

TECHNOLOGY DEMONSTRATION & VALIDATION (6.3)

- GROUND TESTS
- FLIGHT TESTS
  - PRIMARY
  - SECONDARY (UNRELATED TO PRIMARY MISSION, e.g. ACTEX)

TECHNOLOGY INSERTION

MCDONNELL DOUGLAS

- MATURE - READY FOR LOW RISK INSERTION
  - EXTENSIVE GROUND TESTS
- TIME PHASED WITH SYSTEM DEMO PROGRAM
- SYSTEM DESIGNERS PARTICIPATE IN TECHNOLOGY DEVELOPEMENT ("OWNERSHIP")
- GROUND TESTING BY SAME PERSONNEL & FACILITIES AS SYSTEM ACCEPTANCE TEST
- ALL SYSTEM "-ILITIES" ADDRESSED
- FAIL-SAFE OPERATION MEANS "TRANSPARENT" TO SYSTEM

22

ADAPTIVE THERMAL ISOLATOR EXAMPLE

MCDONNELL DOUGLAS

GROUND RULES

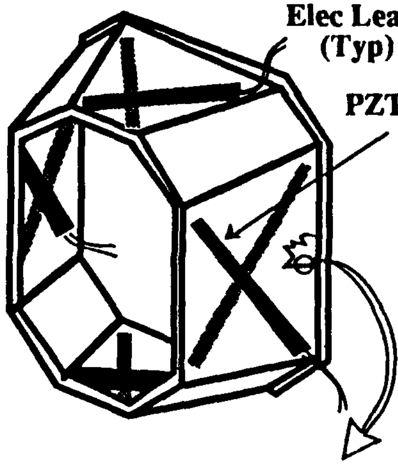
- MEET ALL SYSTEM REQUIREMENTS:
  - SCHEDULE
  - RELIABILITY
  - MANUFACTURING
  - SYSTEM INTEGRATION
  - SURVIVABILITY & LIFE CYCLE
- DESIGNS INTERCHANGEABLE
- INTERFACE WITH ALL HARDWARE
- FAILSAFE PERFORMANCE
- USE SAME TEST PROCEDURES, FIXTURES, & PERSONNEL

CANDIDATE ATI DESIGNS

MCDONNELL DOUGLAS

ADAPTIVE STRUCTURES & COMPOSITE MATERIALS IMPROVE THERMAL & DYNAMIC PERFORMANCE

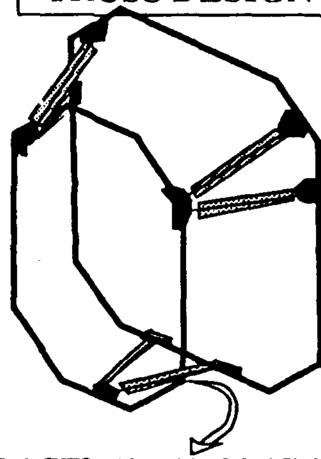
SHELL DESIGN



• SANDWICH CONSTRUCTION

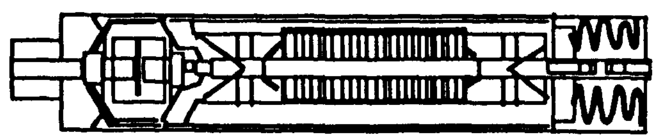
• MONOCOQUE CONSTRUCTION

TRUSS DESIGN



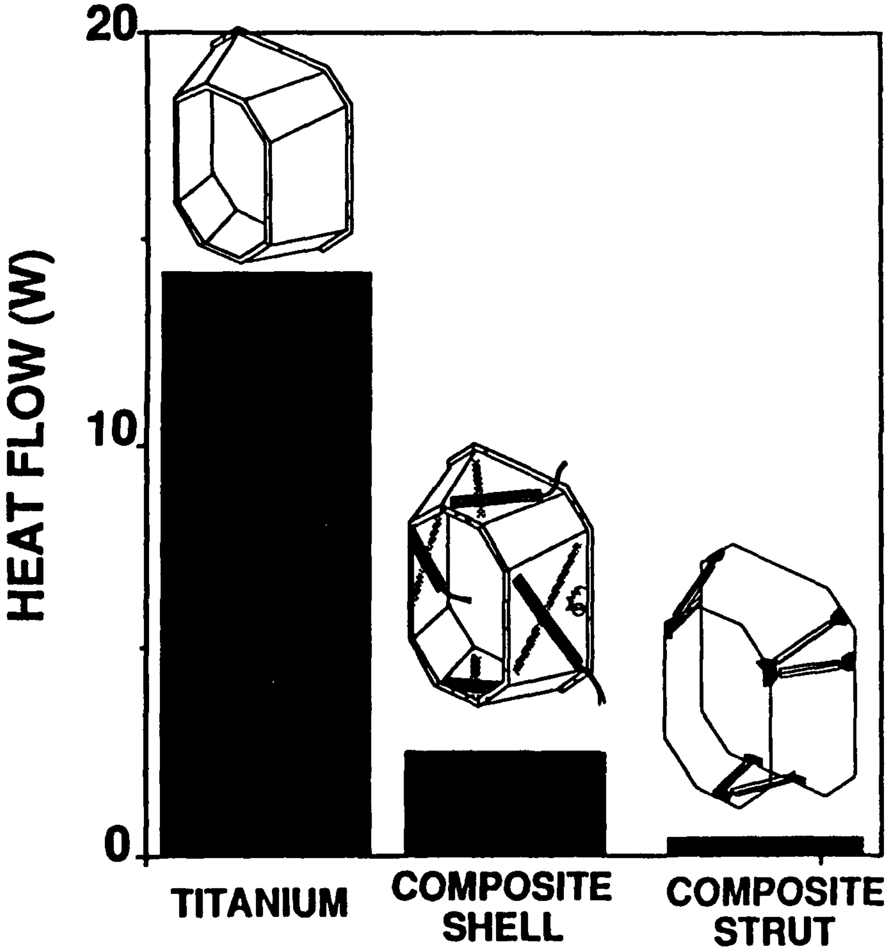
MDSSC ACTIVE DAMPING STRUT

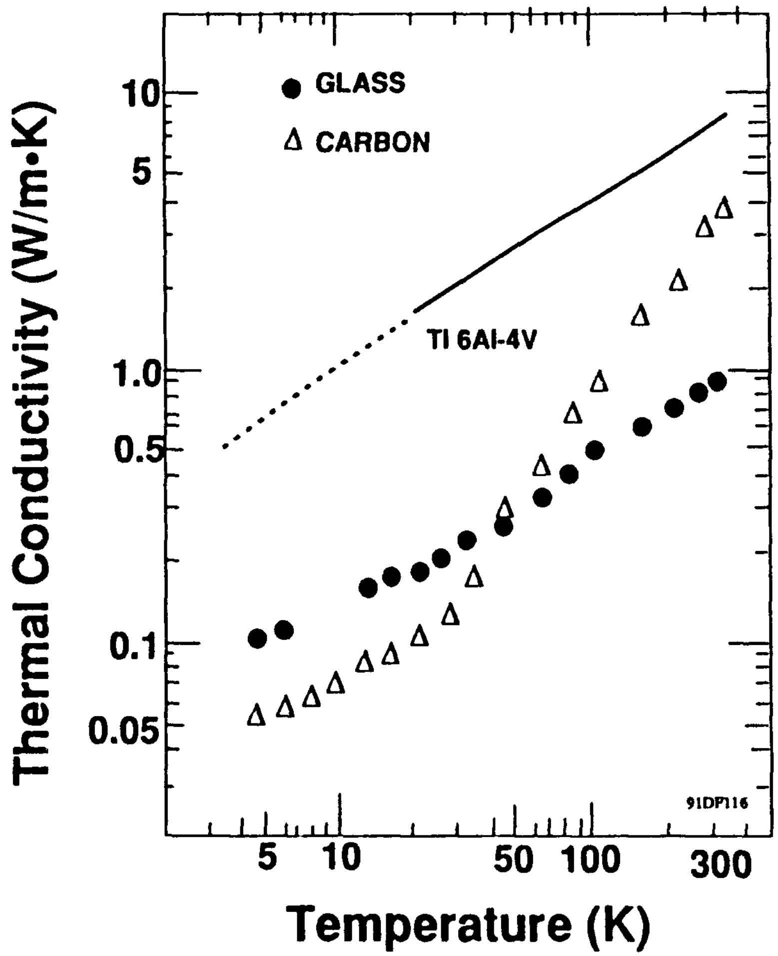
JPL ACTIVE MEMBER



ATI DESIGNS PROVIDE IMPROVED THERMAL ISOLATION

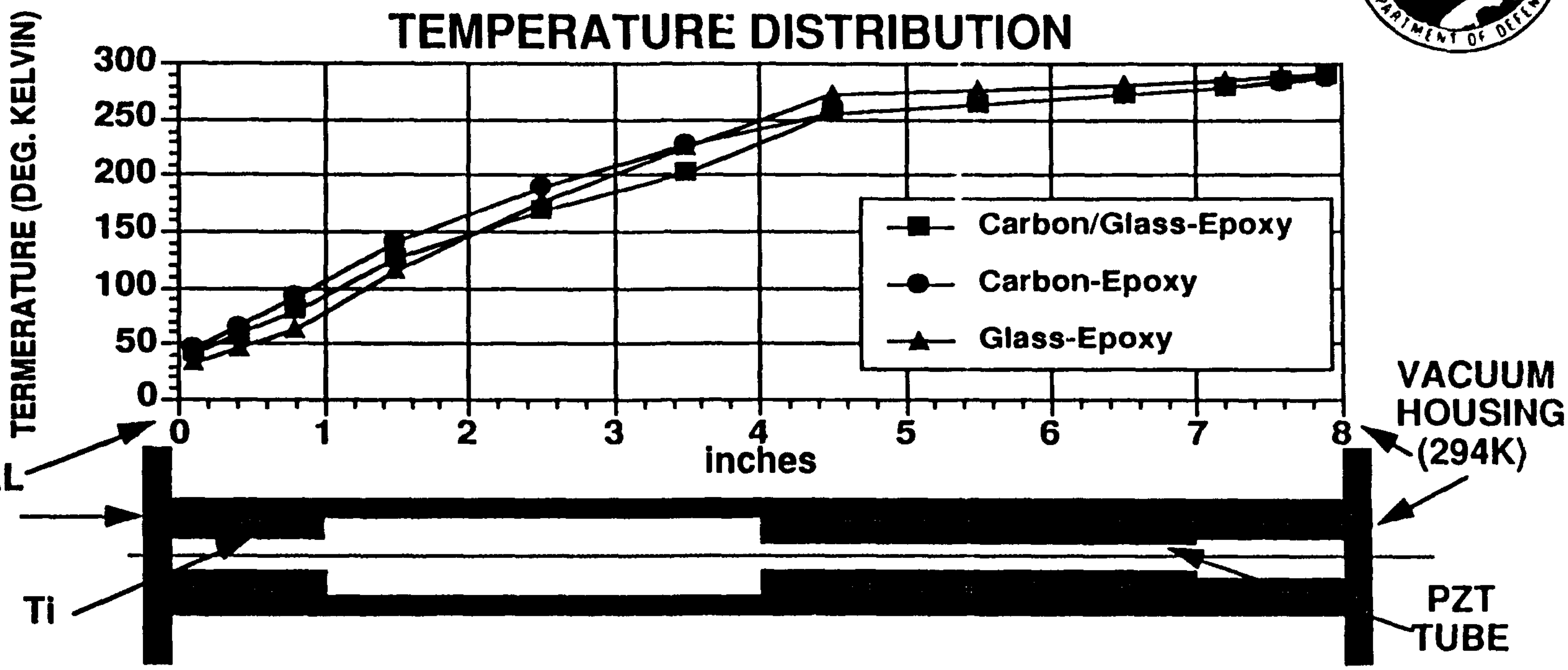
MCDONNELL DOUGLAS

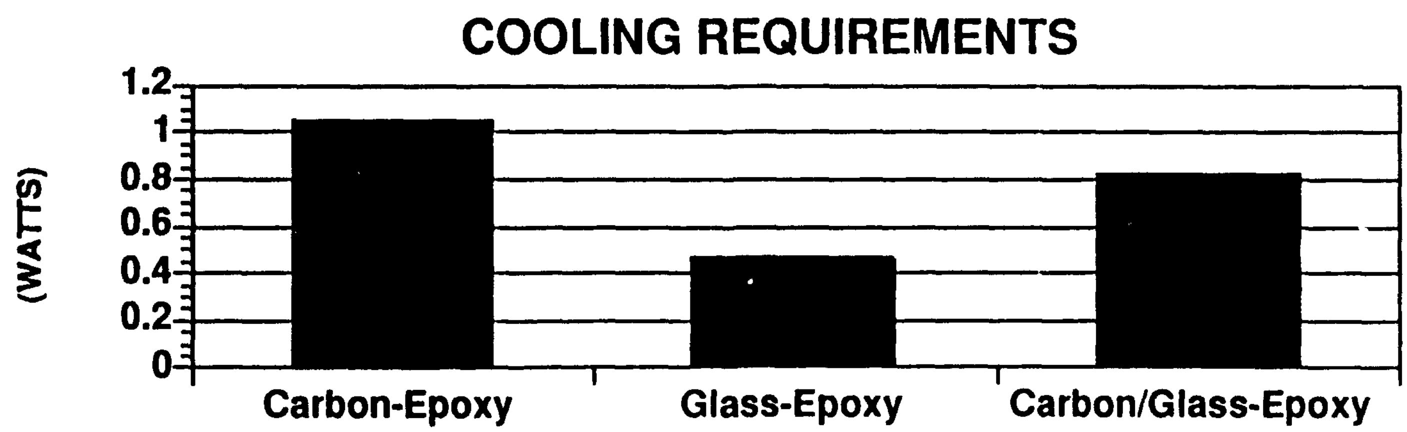




ATI STRUT DESIGNS MEET SENSOR REQUIREMENTS

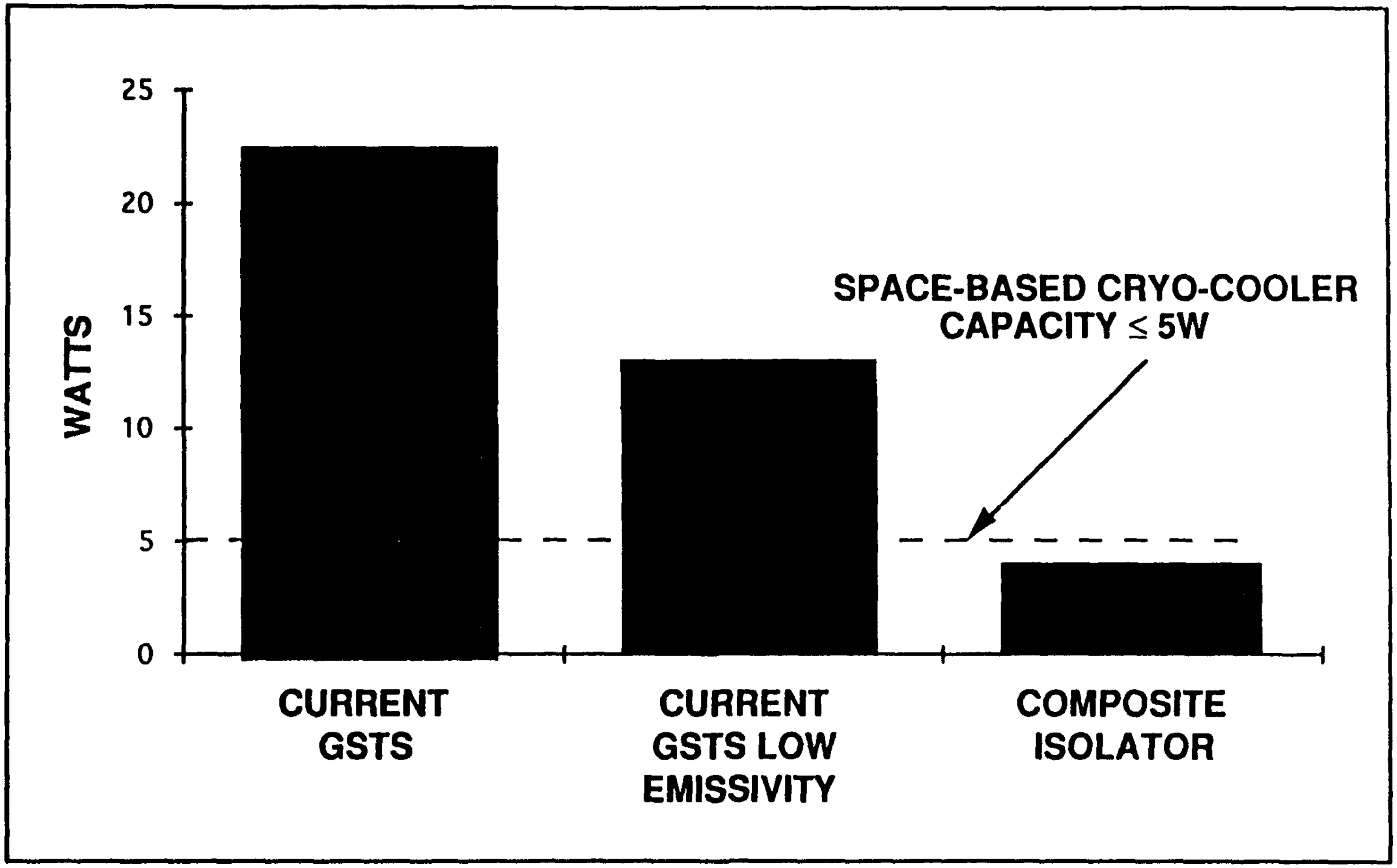
MCDONNELL DOUGLAS





A COMPOSITE ISOLATOR IS REQUIRED FOR SPACE-BASED SENSORS

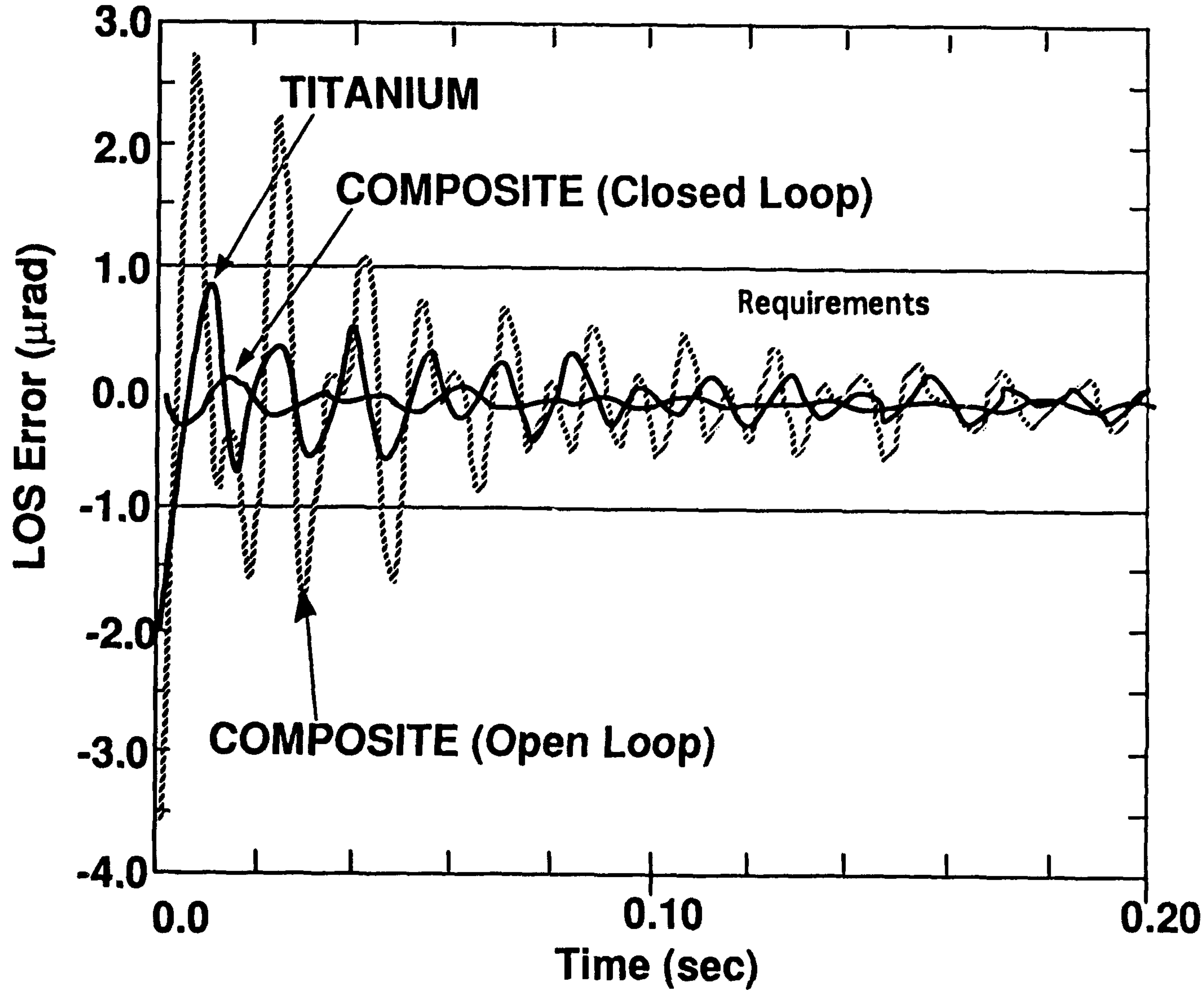
MCDONNELL DOUGLAS



TOTAL COOLING REQUIREMENT FOR COOLER AT ≤ 40K

ATI DESIGN IMPROVES LOS PERFORMANCE

MCDONNELL DOUGLAS



SUMMARY

TO PROVIDE MISSION-ENABLING TECHNOLOGY ...

- TIE-IN TO SYSTEM DESIGNERS TO UNDERSTAND EXISTING SYSTEM
- UNDERSTAND & ACCOMMODATE ALL SYSTEM REQUIREMENTS
- PROVIDE TECHNOLOGY AT LOW RISK WITH VALIDATED FAILSAFE CAPABILITIES

HARDWARE DESIGN PROBLEMS

presented by
R.L. ROBINSON
Jet Propulsion Laboratory

10 February 1993

Advanced Sensory Spacecraft
Structures Workshop

Institute for Defense Analyses
Alexandria, Virginia

AGENDA

- A PERSPECTIVE
- DIFFICULTIES IN DETAIL
- AN APPROACH

In small technical research satellites **there's never enough**

- power
- packaging volume
- mass allotment
- schedule

a law of God perhaps not, but certainly a fact of life

DIFFICULTIES

STRUCTURAL ACTUATOR AMPLIFIER/DRIVER

- EXTREME POWER TRANSFER EFFICIENCY REQUIRED
  (Actuators normally highly reactive, Many require offset biases, Thermal conductivity paths compromised, High voltages required)

- BANDWIDTH/STABILITY REQUIREMENTS
  (Wide bandwidth actuator requirements complicate loop stability designs, Area/Surface mount actuators include performance non-linearities and variations due to physical attachment techniques)

- S/C POWER SYSTEM ISOLATION/GROUNDING PROBLEMS
  (Complicated by the field/surface effects of embedded area actuators)

DIFFICULTIES

SENSORS/SIGNAL PROCESSING

- NOISE
  (Synchronous/Non-Synchronous, Analog/Digital, Conducted/Radiated, the environment is changed)

- TRACKING REQUIREMENTS
  (To optimize actuator system performance over environment variation range induced changes)

- MEASUREMENTS/DIAGNOSTICS
  (Built-in diagonstics and self-calibration now become on agenda requirements)

APPROACH

AS EXPERIMENT SYSTEM DEVELOPERS, WE NEED TO RECOGNIZE THAT THE FOCUS TOWARDS MORE INTEGRATED STRUCTURE/ACTUATOR/SENSOR IMPLMENTATIONS MANDATES THAT SYSTEM PERIPHERAL SUPPORT FUNCTIONS AND HARDWARE DEVELOPMENT CAN NO LONGER BE CONSIDERED "Just another design task" IN THE SERIAL FLIGHT EXPERIMENT SYSTEM HARDWARE PATH.

WE CAN'T CONTINUE TO HAVE A MINDSET WHICH SAYS "Take the laboratory test instrumentation (setup) and make it smaller so we can fly".

WE NEED TO COMPLEMENT THE EXPERIMENT DESIGN PHASE WITH THE REALIZATION OF THE REAL REQUIREMENT FOR APPLICABLE AND AVAILABLE HARDWARE IMPLEMENTATIONS.

BOTTOM LINE

RECOGNIZE THAT PERIPHERAL SYSTEMS HARDWARE NEEDS DEVELOPMENTAL TIME AND SUPPORT IN COORDINATION WITH THE NEW TECHNOLOGY SMART STRUCTURES ....

SPACECRAFT MASS MINIMIZATION BY SUBSYSTEM OPTIMIZATION

J.A. McKay
Research Support Instruments
Hunt Valley, MD and Alexandria, VA

Workshop on Advanced Sensory Spacecraft Structures
Institute for Defense Analyses
10 February 1993

S/C MASS MINIMIZATION STRATEGY

Two-phase approach to spacecraft mass minimization:

- Merge sensors, interface electronics, and structural elements into single multifunction, lightweight component
  - Optimize sensor/interface circuit support structure for maximum strength to mass ratio
  - Electronics on faces must have ≈megarad survivability

- Pack signal processing electronics into single, minimum volume block
  - Optimize electronics module for maximum functionality per unit volume and mass
  - Objective: permit the use of high density, high performance, high functionality integrated circuits, even though not capable of surviving hundreds of kilorads

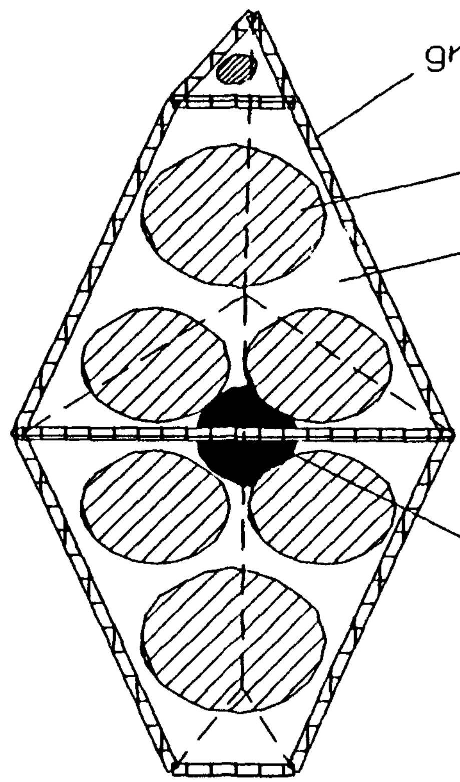
OPTIMIZED SUPPORT STRUCTURE

- Graphite epoxy frame for maximum strength with minimum mass; optimized for structural behavior

- Faces made of flexible circuits to integrate sensors and interface electronics; optimized for support of sensors and circuitry

- Liability: requires extremely rad hard interface electronics

  - Putting all of electronics on faces puts severe limits on parts selection



OPTIMIZED ELECTRONICS CONFIGURATION

- Based on a defensive technique devised against NPBs:
  - Collect all electronics into a single, compact volume
  - Hide this behind largest available structural mass

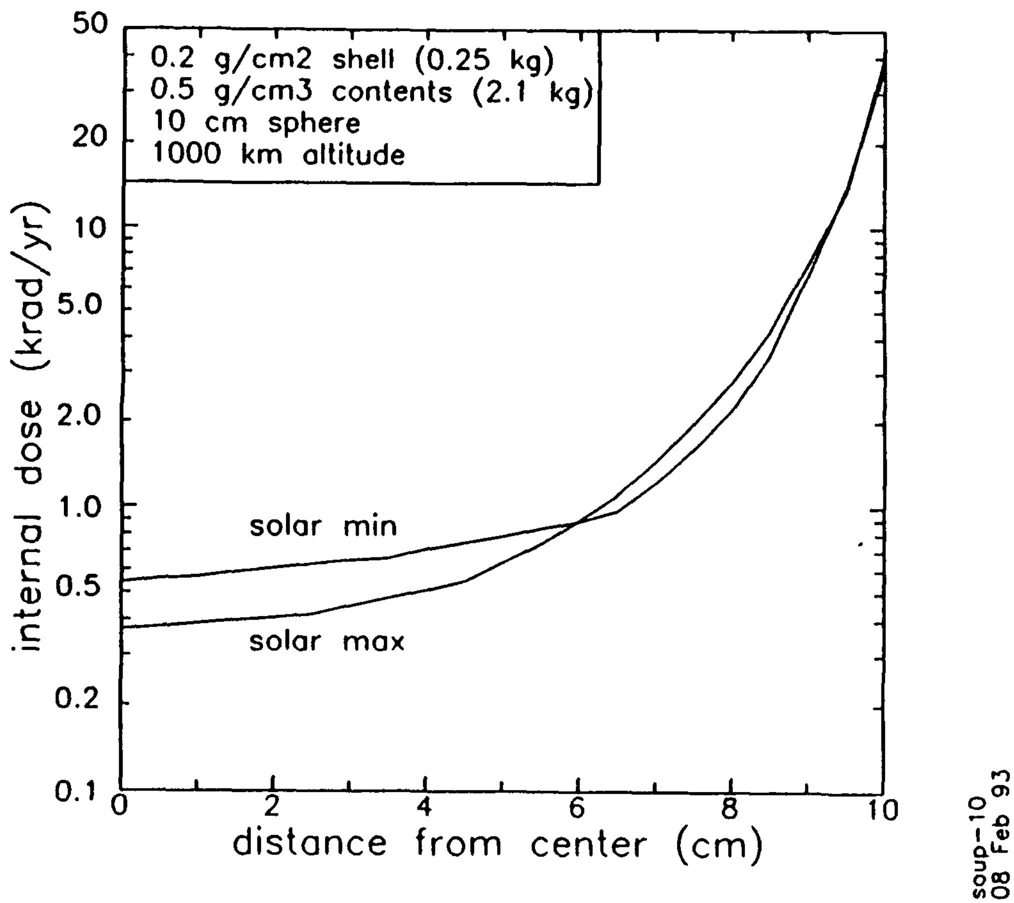
Adapted for ultralight, low-mass spacecraft in natural radiation environment:

- Use highest density, highest functionality electronics devices to minimize parts count, dimensions
  - ASICs, PGAs, highly integrated microcontrollers
  - Generally <u>not</u> rad hard, but can be radiation tolerant ($\approx$10 krads)

- Collect all S/C electronics into a single, ultracompact avionics module
  - Parasitic shield mass will be minimized, and can be small
  - Mass reduction due to reduced power requirements of non-rad-hard electronics may exceed shield mass
  - Make maximum use of electronics self-shielding

ELECTRONICS SELF-SHIELDING

- Build electronics "brick" with thin EMI shield skin (1/32") -- no dependence on s/c envelope for shielding
- Put intrinsically hard components on outer layer (e.g., connectors)
- Fill next layer with moderately rad-hard components (e.g., line receivers)
- Embed softest components deep in core (e.g., high density CMOS processors, controllers, other logic devices)



S/C MASS MINIMIZATION STRATEGY

- Build truss structure for maximum strength to weight ratio
  - Optimize structural function
  - Fill faces with flexible circuits, sensors, interface electronics
  - Combine sensor support, interface electronics PCB, and cabling functions

- Pack *electronics into single* brick of minimum volume
  - Optimize electronics for functional density
  - Single thin metallic radiation shield of minimum dimensions (EMI barrier)
  - Use intrinsic shielding of electronics connectors, passive devices, other intrinsically rad-hard devices to protect softer internal devices
  - Employ electronics self-shielding to permit the use of rad tolerant, high performance, high density integrated circuits

S/C MASS MINIMIZATION STRATEGY ISSUES

- Capability of ultralight truss + flexible PCB structure to handle vibration loads
    - Subject to drum mode vibrations

- Feasibility of component placement in sequence demanded by radiation capabilities
    - Will conflict with normal circuit layout

Application Specific Integrated Circuit

ASIC

William Krug
(317)353-7964
Naval Air Warfare Center
Aircraft Division, Indianapolis

ASIC ISSUES

SILICON TECHNOLOGIES

TECHNIQUES & METHODOLOGIES

EMBEDDING PROCESS

SHIELDING

SUMMARY

SILICON TECHNOLOGIES

- CONCERNS
  - LIFE EXPECTANCY OF APPLICATION
  - QUANTITY NEEDED
  - BULK EFFECT
  - ION MOBILITY
  - SINGLE EVENT UPSET
- TECHNOLOGIES
  - EPI CMOS
  - FOCUSED ION BEAM
- SILICON FOUNDRY
  - QUALIFIED FOUNDRY PROCESSES
- FEATURE SIZE IMPACTS
  - POWER/FREQUENCY BANDWIDTH

2/9/93

TECHNIQUES & METHODOLOGIES

DESIGN TECHNIQUES (METHODOLOGIES)
- VHDL, STANDARD CELL, GATE ARRAY
- SYNTHESIS, SIMULATION

FUNCTIONAL PARTITIONING
- FUNCTIONS NEEDED
- WHAT FUNCTIONS TO INCLUDE
- WHAT FUNCTIONS CAN BE INCLUDED
- BUILT IN TEST

SIZE REDUCTION
- FINER FEATURE SIZE
- REDUCED PART COUNT
- REDUCED PIN COUNT

EMBEDDING PROCESSES

- ENCLOSURES
  - EMBEDDED
  - CAVITIES
  - ex. VACUUM BOTTLE
- INTERCONNECT
  - FIBER OPTIC
  - CONVENTIONAL
- MATERIALS
  - COMPATIBILITIES
    - PLASTIC/CERAMIC/METAL/COMPOSITE
  - THERMAL EXPANSION
  - BACKGROUND RADIATION LEVELS
- ASSEMBLY PROCESSES
  - PRESSURE
  - TEMPERATURE
  - LAYERING

SHIELDING

LEVEL OF PROTECTION

- METAL FILLED COMPOSITE
- PLATTING
- WOVEN SHIELD LAYERS

LIFE EXPECTANCY

- SHELF LIFE
- ACTIVE LIFE

BACKGROUND RADIATIONS LEVELS

- OHIO SAND VS CHILE SAND

SUMMARY

SILICON FOUNDRIES

QUALIFIED

DESIGN TECHNIQUES & METHODOLOGIES

LIFE EXPECTANCIES, QUANTITIES, FUNCTIONAL PARTITIONING

MATERIALS

SHIELDING, FILL, BACKGROUND RADIATION LEVEL

PROCESSES

HEAT, PRESSURE, LAYERING

APPENDIX D

APPLICATIONS

SAWAFE and

Smart Structures Programs

Bill Saylor

Space Science & Technology Division

Los Alamos National Laboratory

Workshop on Advanced Sensory Spacecraft Structures

Institute for Defense Analysis

10 February 1993

Los Alamos
Space Science & Technology

SKIN SENSOR EXPERIMENT IN SPACE

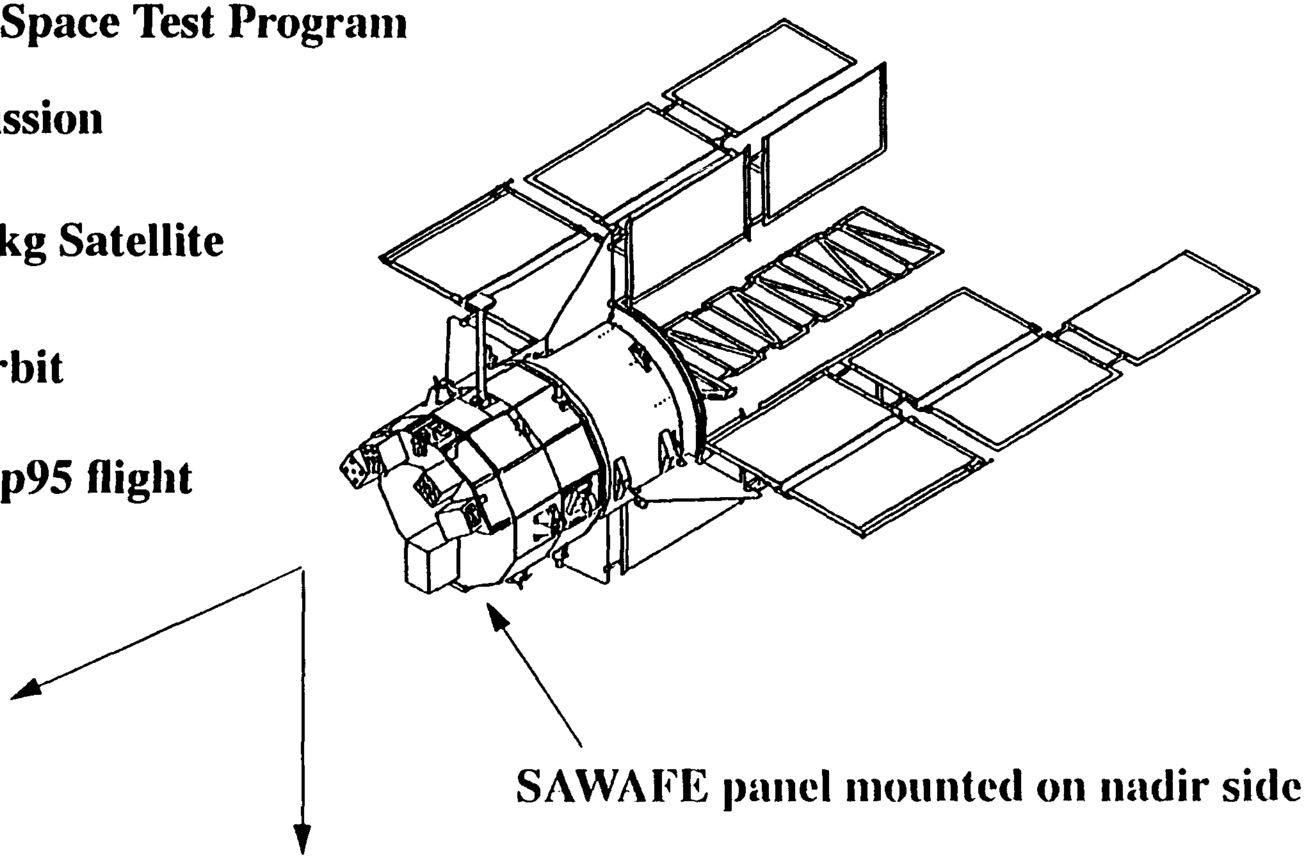
Air Force Space Test Program

STEP3 Mission

TRW 250 kg Satellite

500 km Orbit

Sep94 - Sep95 flight



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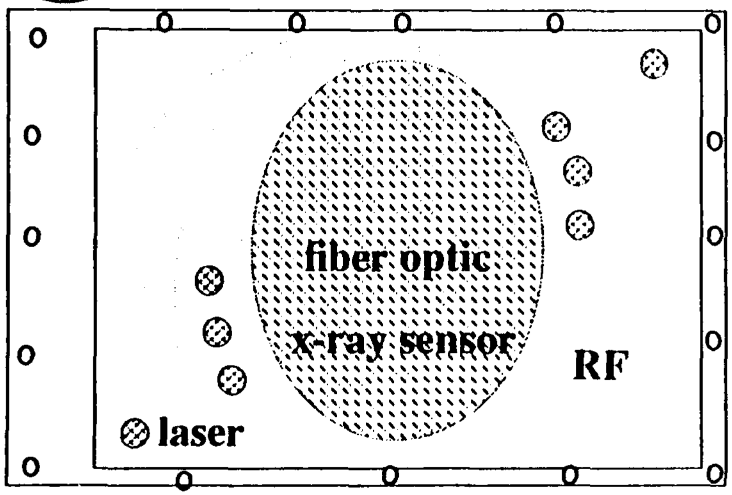
ida.10feb93 pg. 2

SATELLITE ATTACK WARNING AND ASSESSMENT FLIGHT EXPERIMENT

SAWAFE



PMA E1504

PROGRAM OBJECTIVES

SAWAFE program will develop and demonstrate "smart skin" technologies capable of detecting attacks on space assets

Laser, RF, and NUDET sensors will discriminate between background and simulated attack signals

STATUS

SAWAFE is payload on STEP3 mission

SAWAFE detailed design in progress

Continued R&D for follow-on flight experiments

DOE-developed technologies and expertise applied to national need

BUDGET/SCHEDULE/MILESTONES

FY93: $2.6M FY94: $3.2M FY95: $3.3M

CDR is Mar93

Hardware delivery date is Nov93

Launch date is Sep94

Flight Experiment is Oct94 - Oct 95

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Satellite Attack Warning and Assessment Flight Experiment

- **PURPOSE:** ***Provide Warning And Assessment Of An Attack On The Space Element Of A Strategic Defense System***
  - **Define the nature of an attack - where, what physical means, intensity**
  - **Provide awareness of tampering**
  - **Provide collateral information for failure analysis**

- **APPROACH:**
  - **Minimize impact on host system with conformal sensors and minimum mass, power and size**
  - **Fly integrated sensor package on quick reaction spacecraft to validate technologies**

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ida.10feb93 pg. 4

STEP 3 MISSION CONCEPT

OBJECTIVES: *SAWAFE STEP3 mission is to demonstrate "smart skin" technologies capable of detecting attacks on space assets*

- DETECT RADIO FREQUENCY ATTACKS
  - **Discriminate between background, surveillance contacts, targeting, covert interdiction, spoofing, and RF attacks**
- DETECT LASER ATTACKS
  - **Discriminate between background, surveillance contacts, targeting, covert interdiction, spoofing, and laser attacks**
- DETECT NUCLEAR ATTACKS (X-RAY SPECTRUM)
  - **Discriminate between background, remote NUDET, and attack on asset**
- INTEGRATE SENSORS INTO MINIMAL MASS & POWER SYSTEM
  - **Sensor system integrated into spacecraft skins**
  - **Post-processing of sensor data on ground**
  - **Up-load threat assessment algorithms during flight experiment**

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AWA TECHNOLOGY EVOLUTION

SAWAFE 1993
8" x 11" panel
electronics box
data storage
demonstrate
"smart skin"
sensors

Electronics R & D

ASICS, FPGA, MCM, MMIC
flexible PCB's
advanced EW development
high-speed analog processing
pattern recognition & event processing

SAWAFE2
8" x 11" panel(s)
embedded sensor electronics
multi-layer composite panel
demonstrate minimal impact
"smart skin"
sensors

Sensor R & D

laser sensor materials
RF antenna design
CCD / fiber x-ray
rad / particle sensors

AWA Technology Goal
integral sensor panel
embedded electronics
single interface to s/c
intelligent processor
demonstrate
minimal impact, AWA
functional technology

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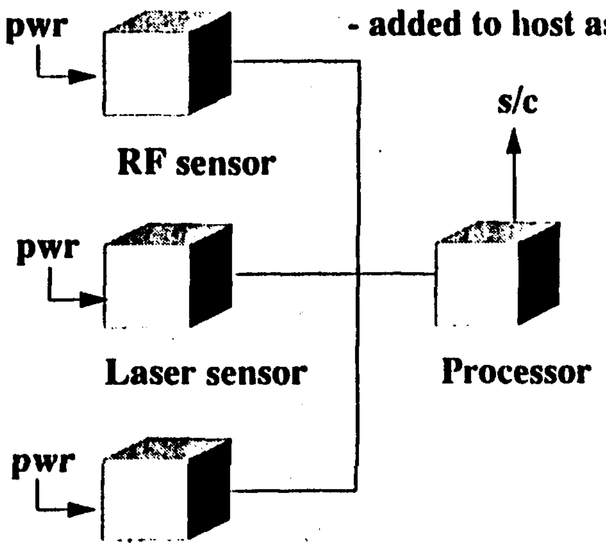
ida.10feb93 pg. 6

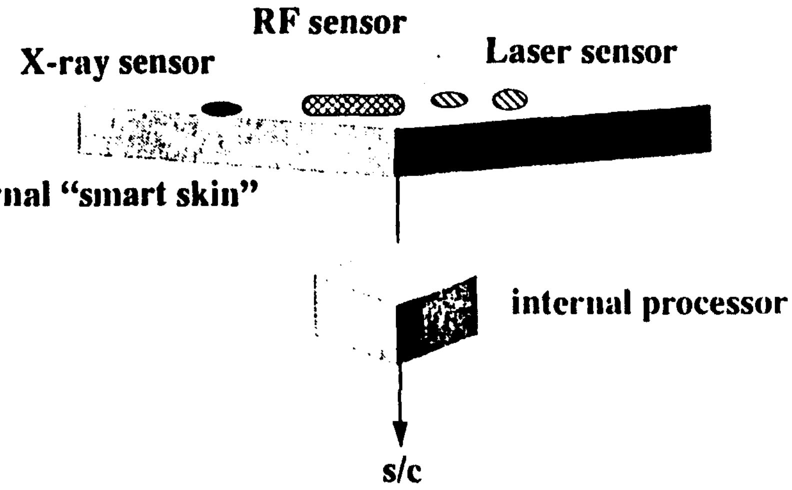
Existing Threat Warning Systems Configuration

- added to host as secondary payloads



Current SDIO Flight Experiment

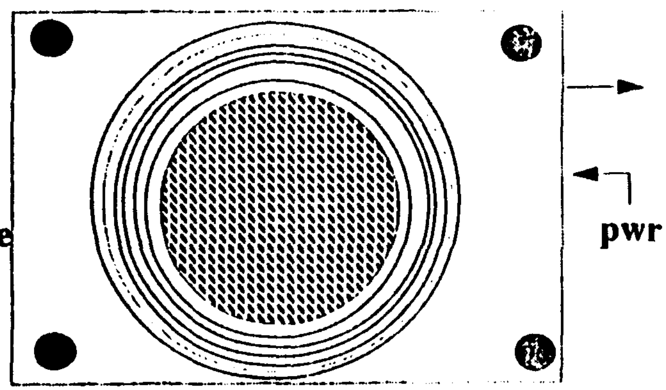
- sensors embedded in structural panel



SAWAFE panel on 1994 STEP3 Mission

Future "Smart Skins" Sensory Panel

laser
RF / HPM
impact
x-ray
temperature
dosimeter
...



panel is conformal, structural part of host
sensors / electronics / processor embedded
autonomous attack warning & assessment
single interface to host processor
single power connection

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ELECTRONICS PACKAGING FOR SMART SKINS

- Leverage Existing Programs in Other Technology Areas
- Packaging That Can Have Fast Turnaround at Reasonable Cost
- Packaging That Can be Made Mechanically Reliable
- Example: Detector Electronics Modules for SSC Main Detector
    - 1 x 2 " HDI package
    - 1280 signal channels input
    - will be produced in quantities of 1000's
    - designed for high radiation dose, severe thermal environment
    - can be repaired during manufacture

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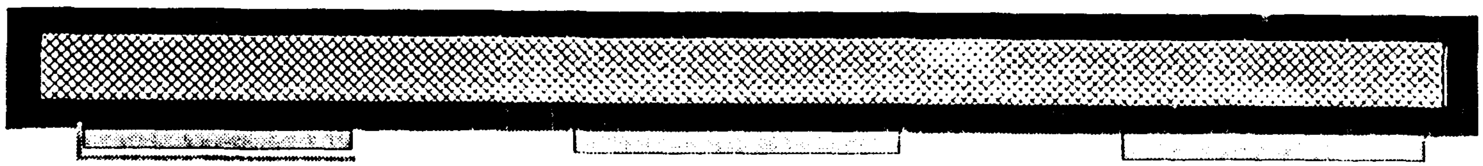
SAWAFE2 PANEL DESIGN

surface-mounted transducers / sensors

fiber-reinforced polycyanate structure with phenolic-impregnated paper honeycomb core



HDI packages adhered to "back" of panel

RFI / abrasion shields over modules

Problems to be solved by mounting substrate:

1. thermal path for HDI modules
2. visco-elastic material to dampen vibrations
3. flexible circuit connections

Benefits to spacecraft:

1. no parasitic mass for electronics box
2. payload conformal to spacecraft structure

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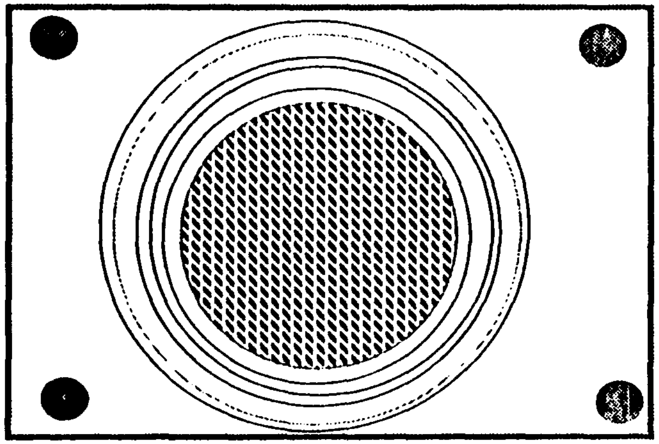
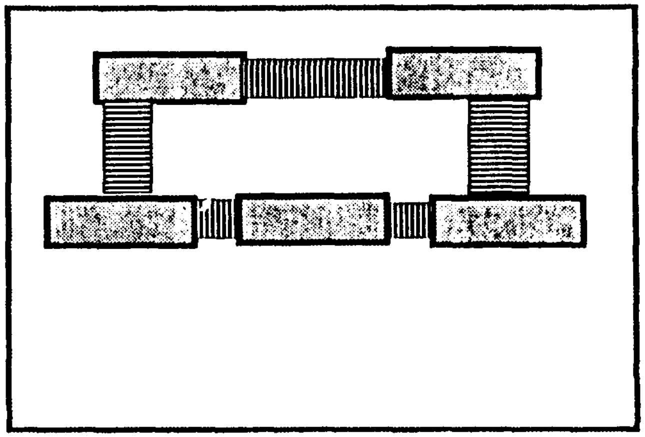
SAWAFE2 PANEL DESIGN

SPACE SIDE OF PANEL



INSIDE OF PANEL



- surface and panel can be curvilinear
- flexible, laser-bonded connectors between HDI electronic modules
- high bandwidth processing in panel / sensor suite electronics
- low bandwidth bus connection to spacecraft
- single power and ground connection to spacecraft

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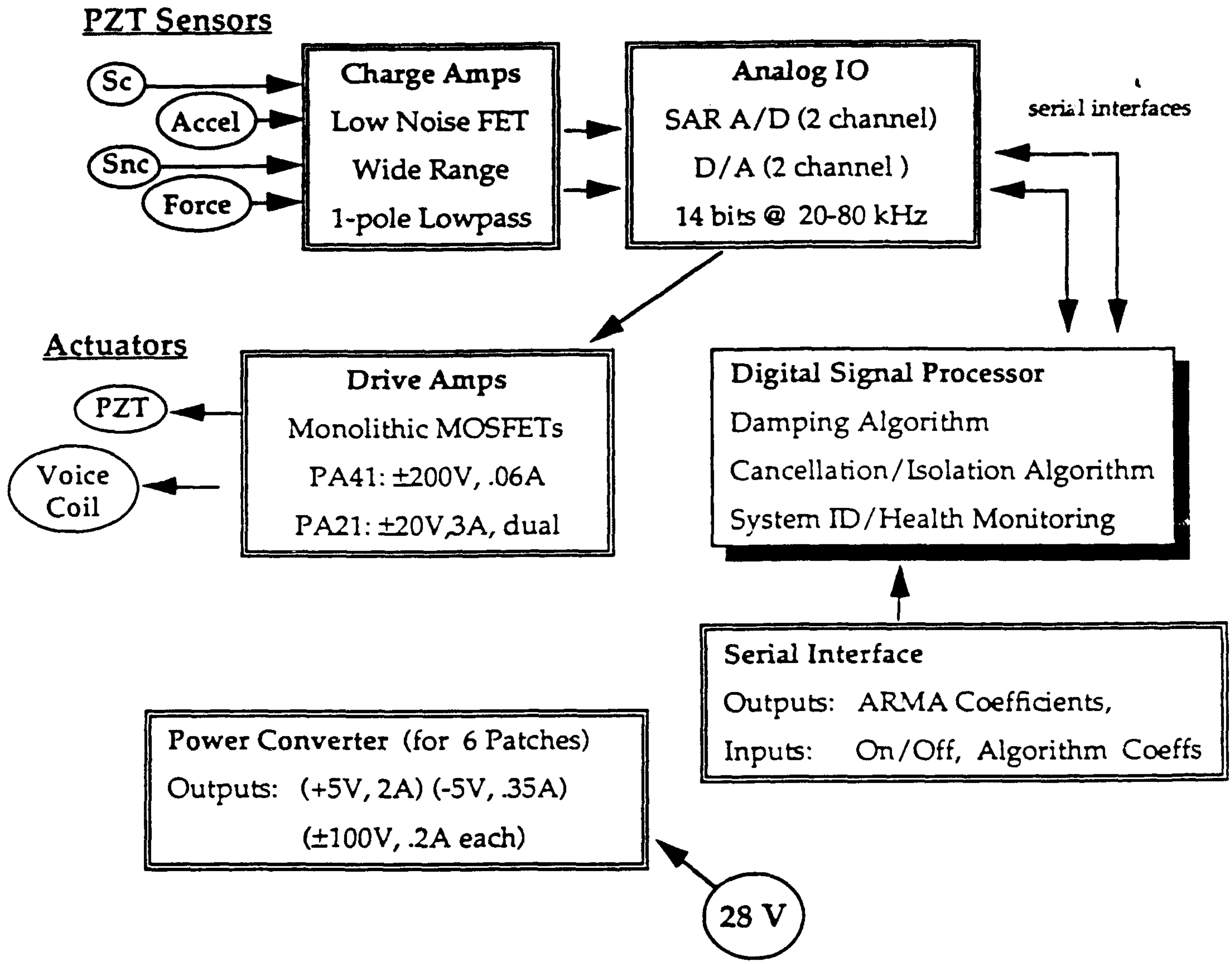
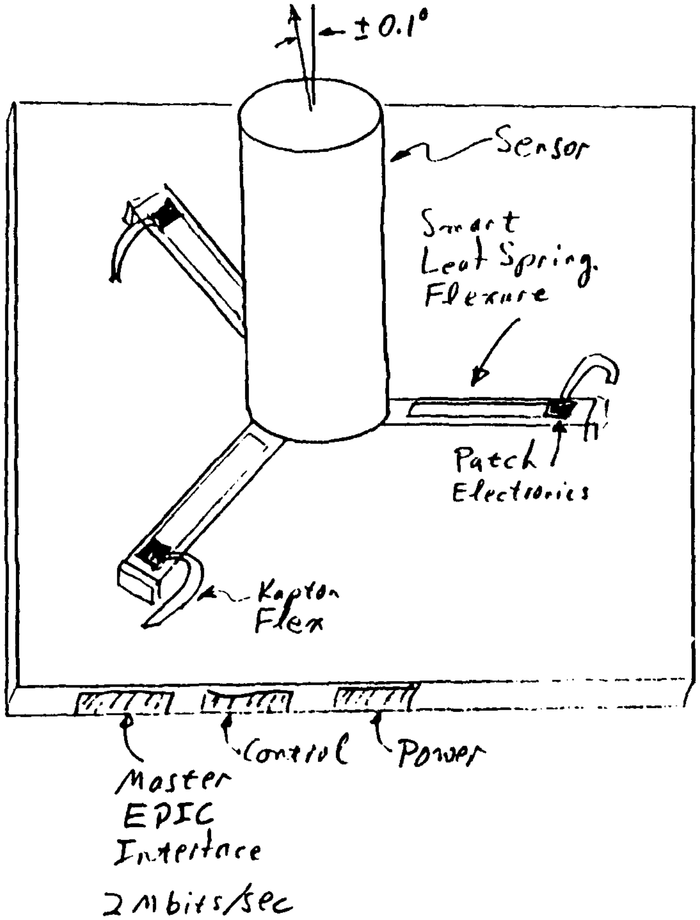
Smart Patch Concept



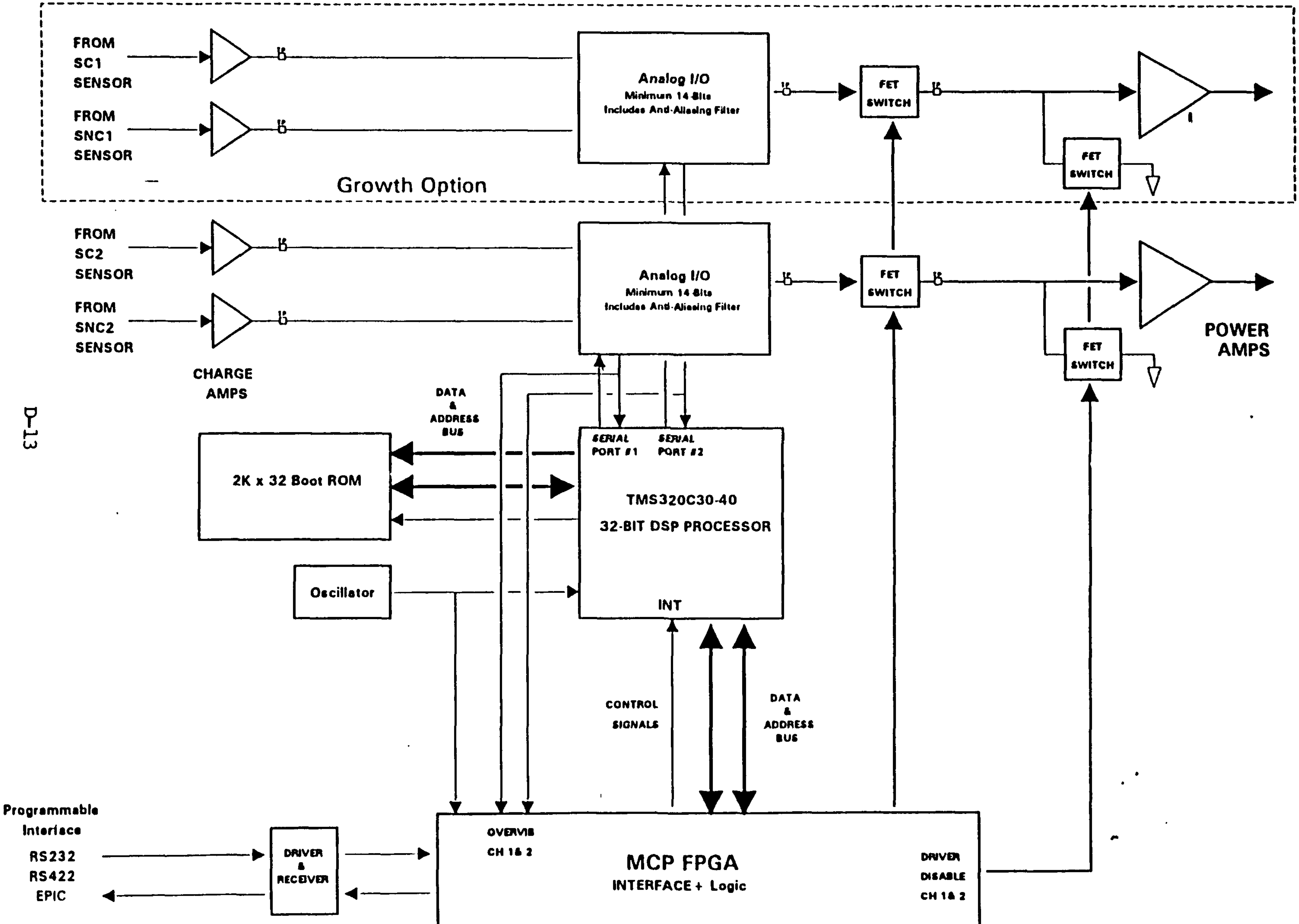
- Developing Space Qualifiable Patch capable of Adaptive Neural Control on MCP contract.
- Candidate Applications include:ACTS, GBI, FEWS, DSP, BP/BE cryocooler
- Miniaturized Vibration Suppression Electronics (MVSE) IR&D aimed at commercial applications
- Candidate applications include: Loudspeakers, Diesel, Turboprops

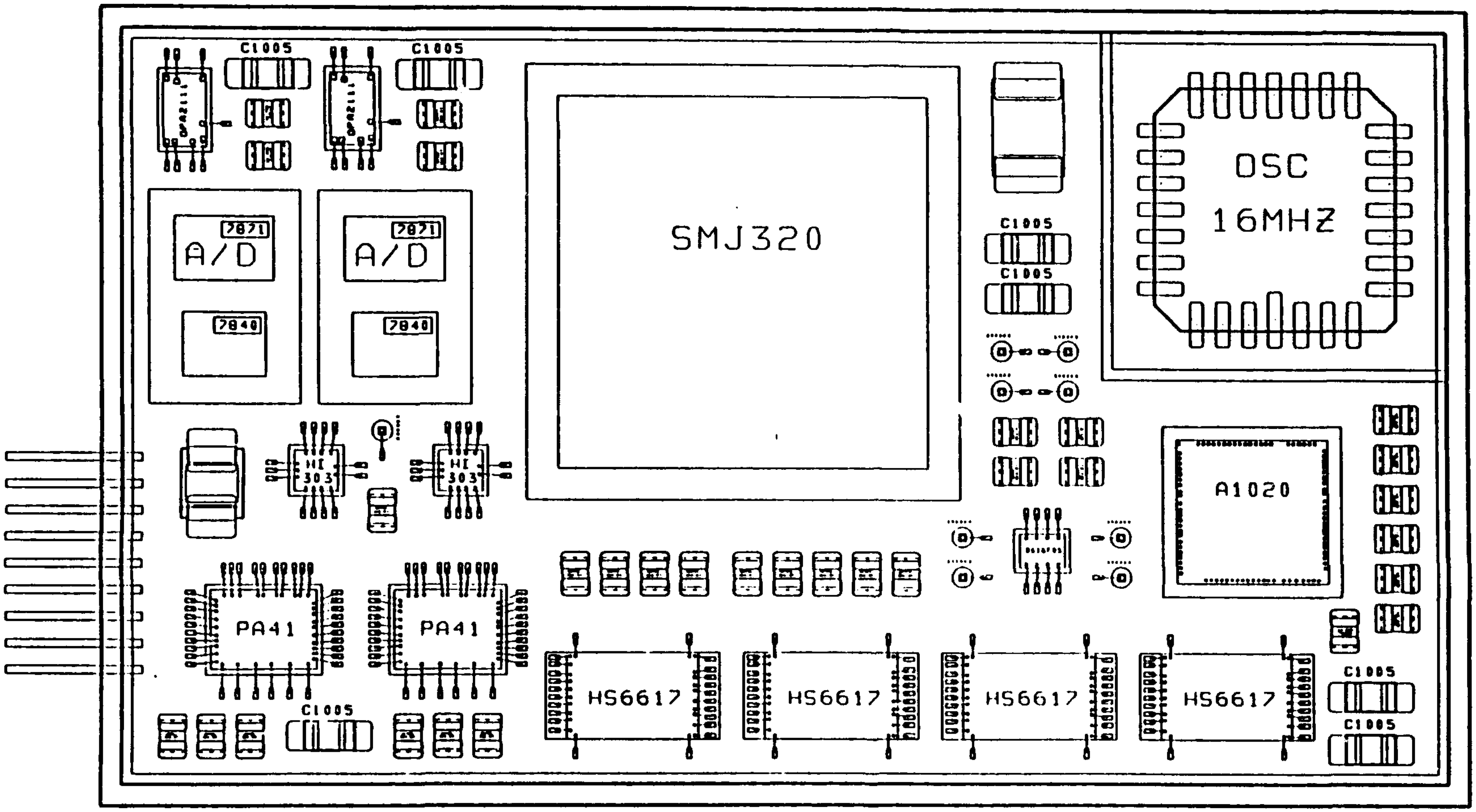
Optical Payload Slice
Micro-Isolation & Pointing



- MicroPointing is Enabling for EOS Multi Sensor Platform
- Coordination between Patch Electronics Can Take Place Using EPIC Data Bus (1 Wire)
- Wiring Bulk Can be Eliminated using Multilayer Printed Flex.
- Electronics Bulk being Reduced using Multi-Chip Module

MCP Block Diagram





MCP

MCM-L
1/21/93
J. LEIBOWITZ

PREPARED J. LEIBOWITZ

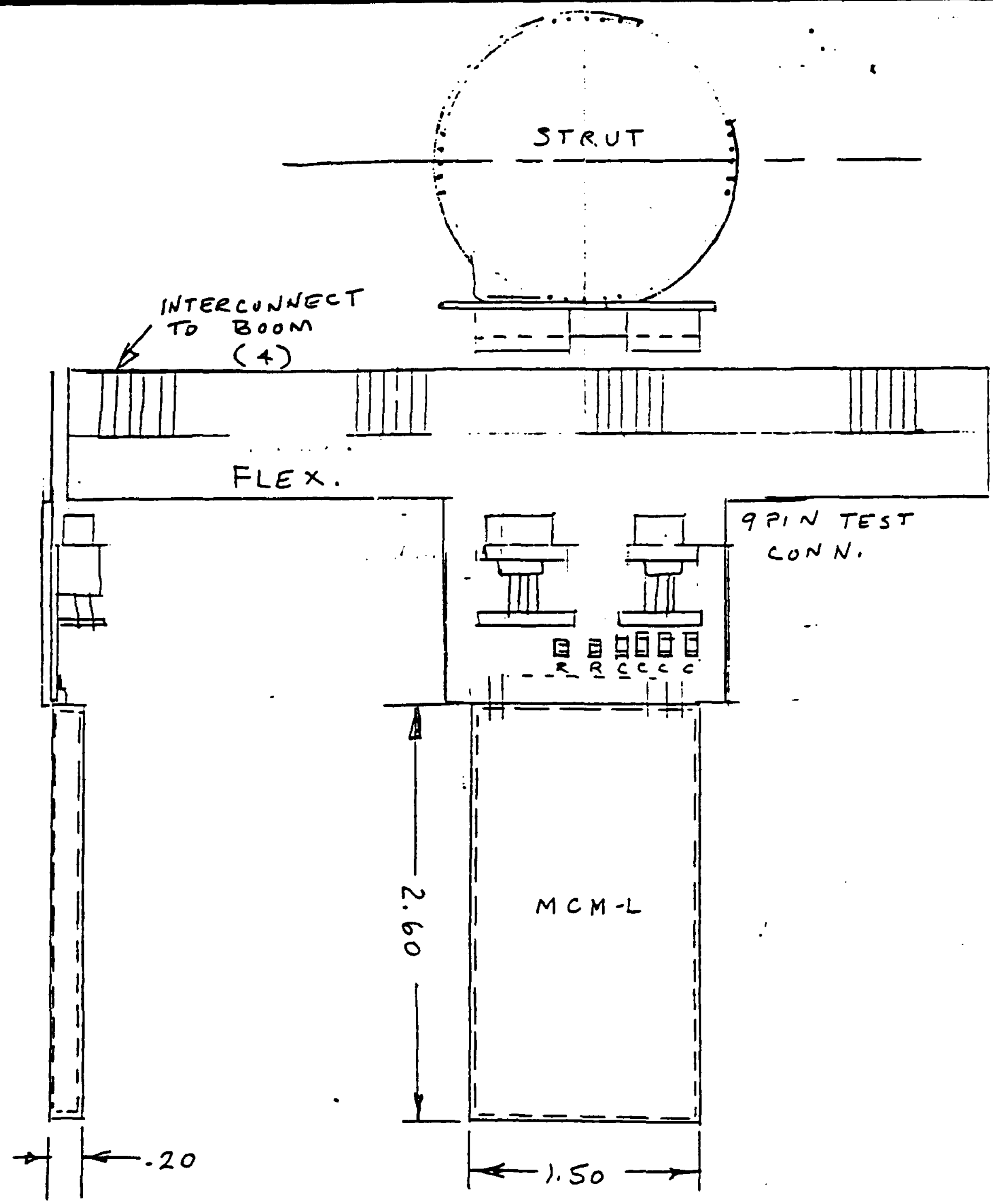
CHECKED

MODEL

REPORT NO.

MCP

PAGE



BP LIFEJACKET
INTEGRATED STRUCTURAL ELECTRONICS

MIKE GALLAGHER
303-977-3682

Workshop Presentation

BP Integrated Electronics Assembly

- BP Overview
- Design Issues
- Why we have DD-9.
- Principal focus of DD-9

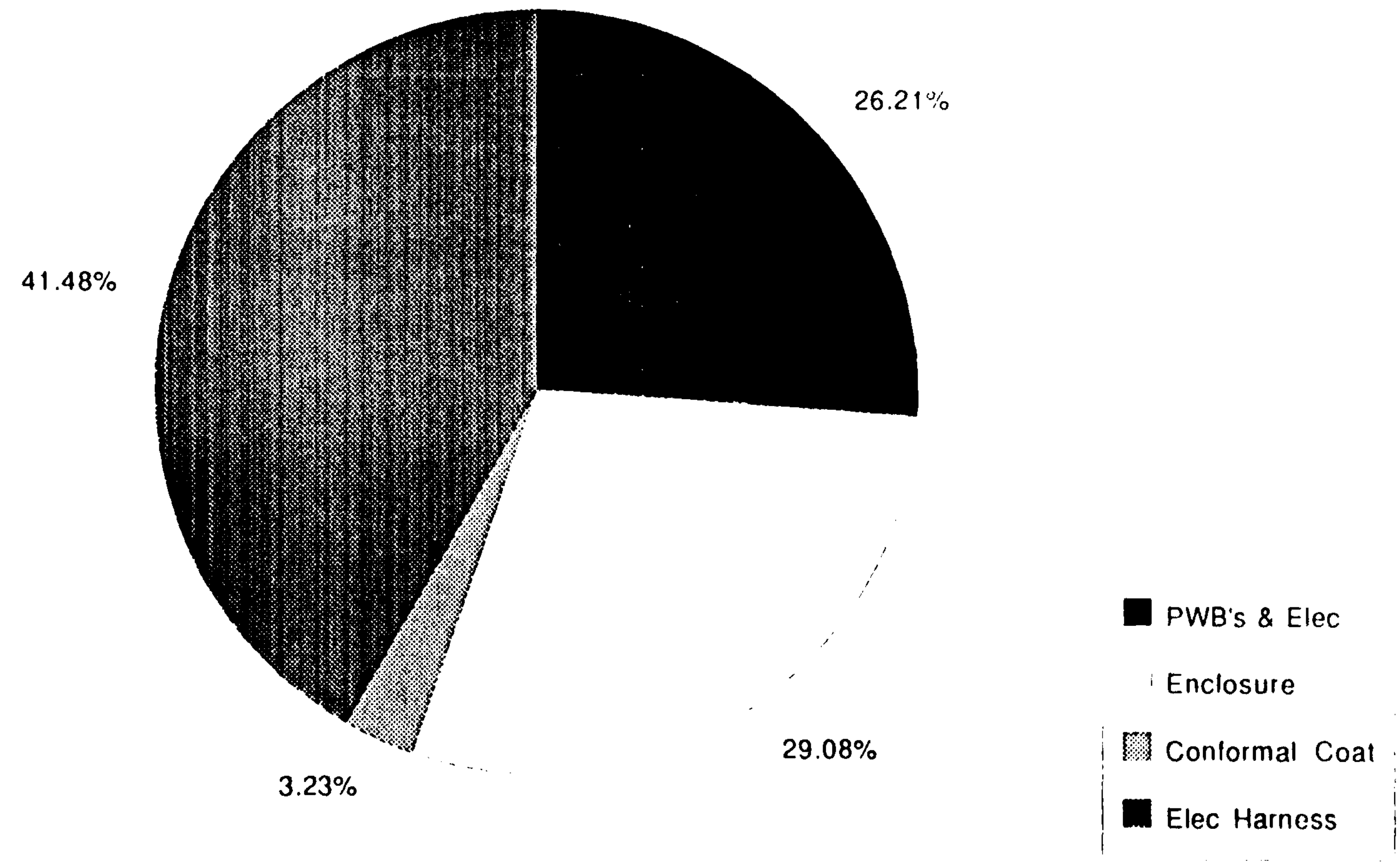
HERITAGE/ BP HISTORICAL PERSPECTIVE

- D-70 D LIGHT SAT IRAD
- FLT 1 SIM Interface Electronics
- FLT 1 KV Electronics Design
- RS 6000 RISC Processor EDU
- FLT 4 C&DH Design
- DD 9 Technology Demonstration

Key Areas in BP Flight Electronics Design

* RISC Processor Interface
* Subsystem Control Electronics
* Data Distribution
* Component Integration

Relative Weight



Integrated Electronics/ Structural Panel

- ***Need: Integrated power distribution and data network.***

  - Directly incorporate power distribution, subsystem control signals, and data distribution in LJ structural panel.

    - Reduced mass
    - Less touch labor
    - Decrease required volume
    - Increase packing density
    - Increase modular design
    - Reduced routing complexity

Design Requirements

Integrate hardware and software components of BP Lifejacket into a light-weight, space qualified network of processors, sensors, actuators and other components.

Key Functional Requirements:

Provide basic mission data processing, command and subsystem control to meet BP mission in a long term space environment, to include:

1) RISC based processing

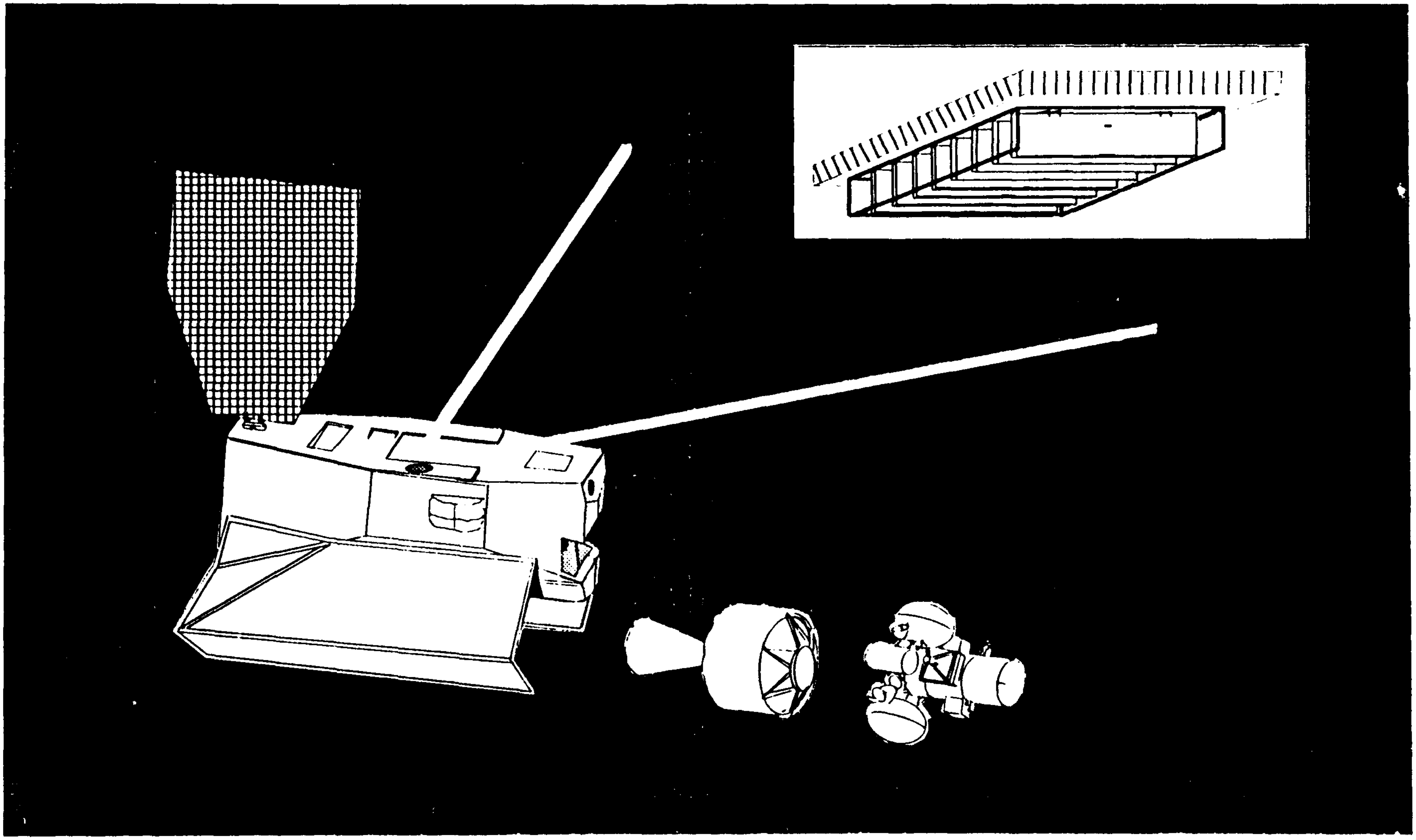
2) Lifejacket configuration control

3) Lifejacket integrity

4) Data distribution

Requirements span from RISC processor unit to individual components; complex sensors, comm, GN&C, GPS, ordnance control devices, temp monitors etc

TOP DECK CUTAWAY



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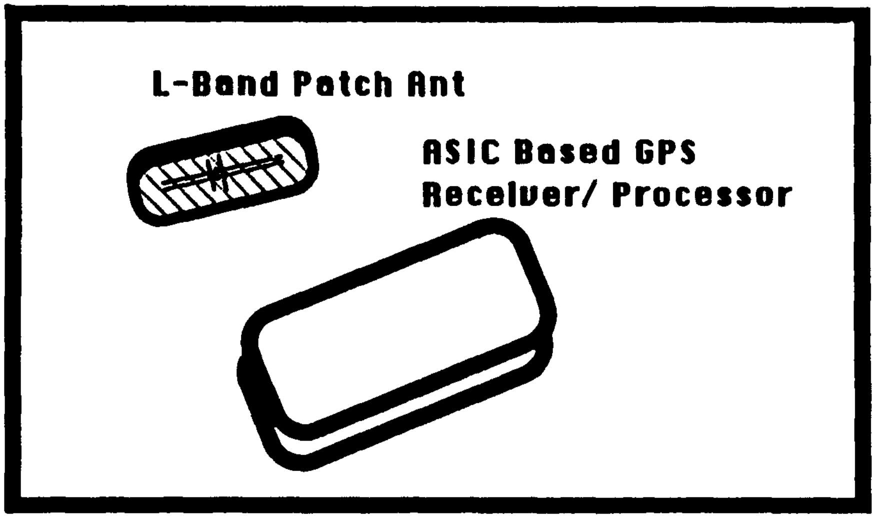
DWG 2

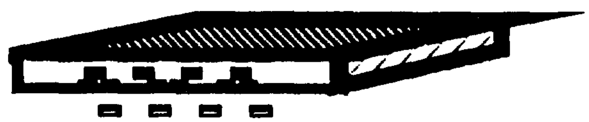
Lifejacket Application Areas

	Power	Control	Data
Sensor Subsystems			
E-O Mech/ Elect	X	X	X
Comm Ant/ Elect	X	X	X
GN&C Components			
IMU	X		X
GPS (Rcvr/Proc)	X		X
Reaction Wheels	X	X	
Torque Rods		X	
Magnetometer	X		X
Survivability/ Integrity	X		X

DD-9 EXAMPLE SOLUTIONS

Solutions range from RAD 6000 3-D Hybrid Packaging, custom GPS Ant/ RPA integration to shape memory controllers.





Solution A:
Conventional Harness,
RF coax and Connectors,
a) power
b) data
c) control

Solution B:
Embedded patch antenna,
integral RF distribution,
light weight power, data
and control signal distribution.

DD-9 INTEGRATED DESIGN APPROACH

Conventional

- Independent Effort
- Isolated from S/C design
- Ad Hoc installation of Black Boxes
- Extensive cabling
- Planar electronics
- 25 year old 'aircraft ' type technology

2-D Electronics
3-D Boxes & Cables
Low volumetric efficiency
High mass
Complex assembly

Integrated

- Multi-Discipline design (HW/ SW)
- Common design tools
- Optimize use of VHDL VHSIC technologies
- 3-D Hybrid Packaging
- Built in self test
- Modular assembly
- Limited field test & maintenance
- Small, light weight

3-D micro electronics
2-D/conformal packaging
High volumetric efficiency
Low mass
Modular Assembly

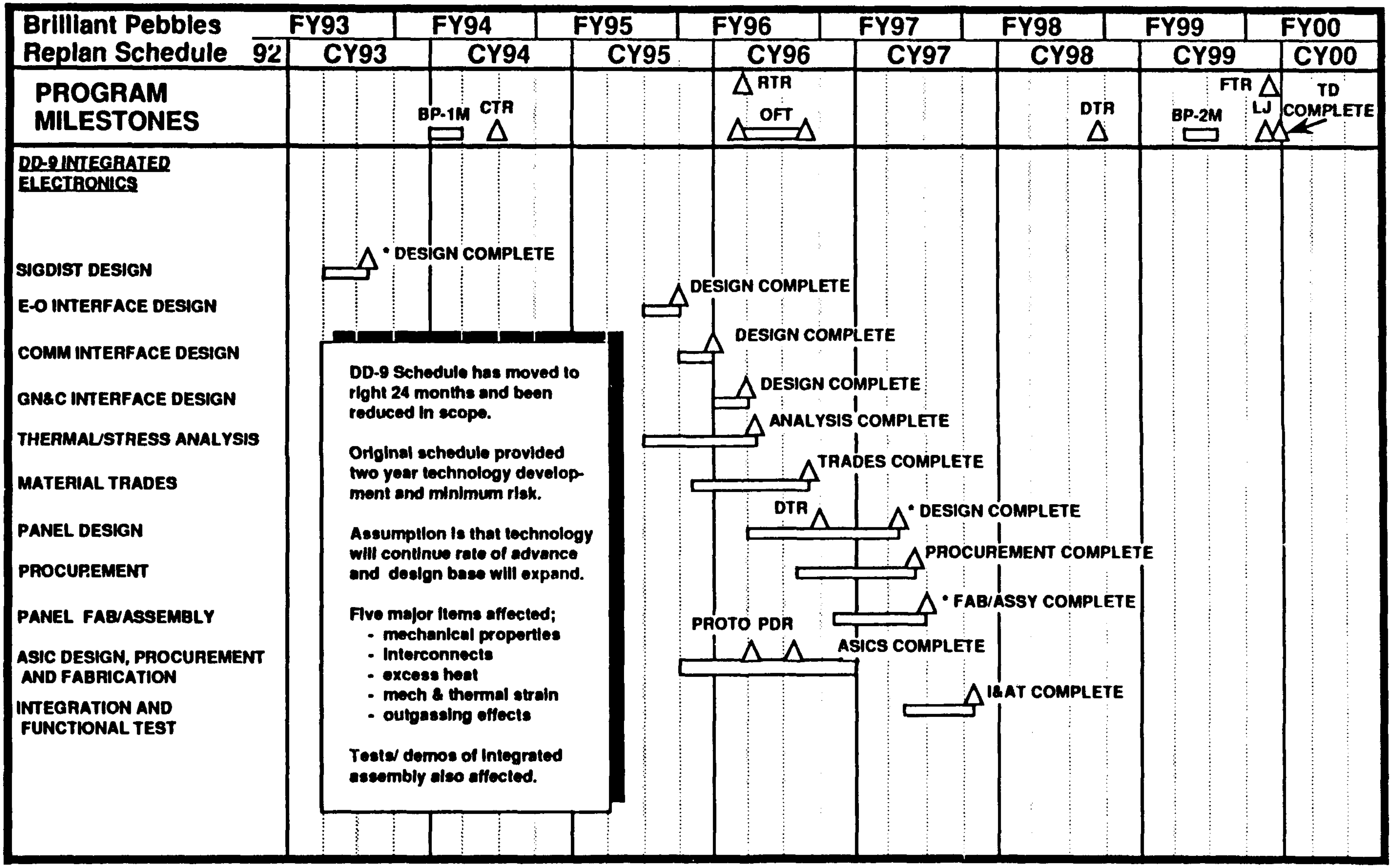
DD-9 CTI / OC Original Concerns

	CTI/ OC Item ADDRESSED	TECHNOLOGY SHORTFALLS	DEMONSTRATIONS REQUIRED
Integrated Radiator/ Electronics/ Structure	CTI: 4.0 Station Keep 5.1 Station Keep 5.5 ACS 5.6 LJ TCS 5.9 Int'd R/E/S 5.10 Int'd Shield 7.0 Survivabilty 10.0 Comp's + SW OC's: 1.0 Performance 4.0 Survivability 5.1 Reliability 5.2 Maintainability 5.3 Service Life 6.2 Health/ Status 8.9 Producibility	Mechanical property characterization of electronics materials and inherent survivability gains for electronics from structural materials. Effects of mechanical and thermal strain on embedded power distribution networks have not been quantified. Removal of excess heat from electronics into adjacent structure not demonstrated. Interconnects between 3-D package and structural network has not been demonstrated.	Mech'l Engr use of EE design and analysis tools. Data transfer methods between tools. Quantify electronics performance degradation and life concerns due to introduction of mechanical strain. Quantify additional structural failure modes and life concerns due to integration of electronics with structure. Production process development and validation of production cost, repeatability, reliability, accessibility and maintainability.

SPECIFIC DESIGN ISSUES

- Launch environment, shock, vibration, g loads..
- On orbit life, thermal stress, radiation, particle impacts, outgassing...
- Platform level autonomy for GPS navigation, power management, thermal control, timing...
- Maintenance & producibilty concept

DD-9 INTEGRATED ELECTRONICS

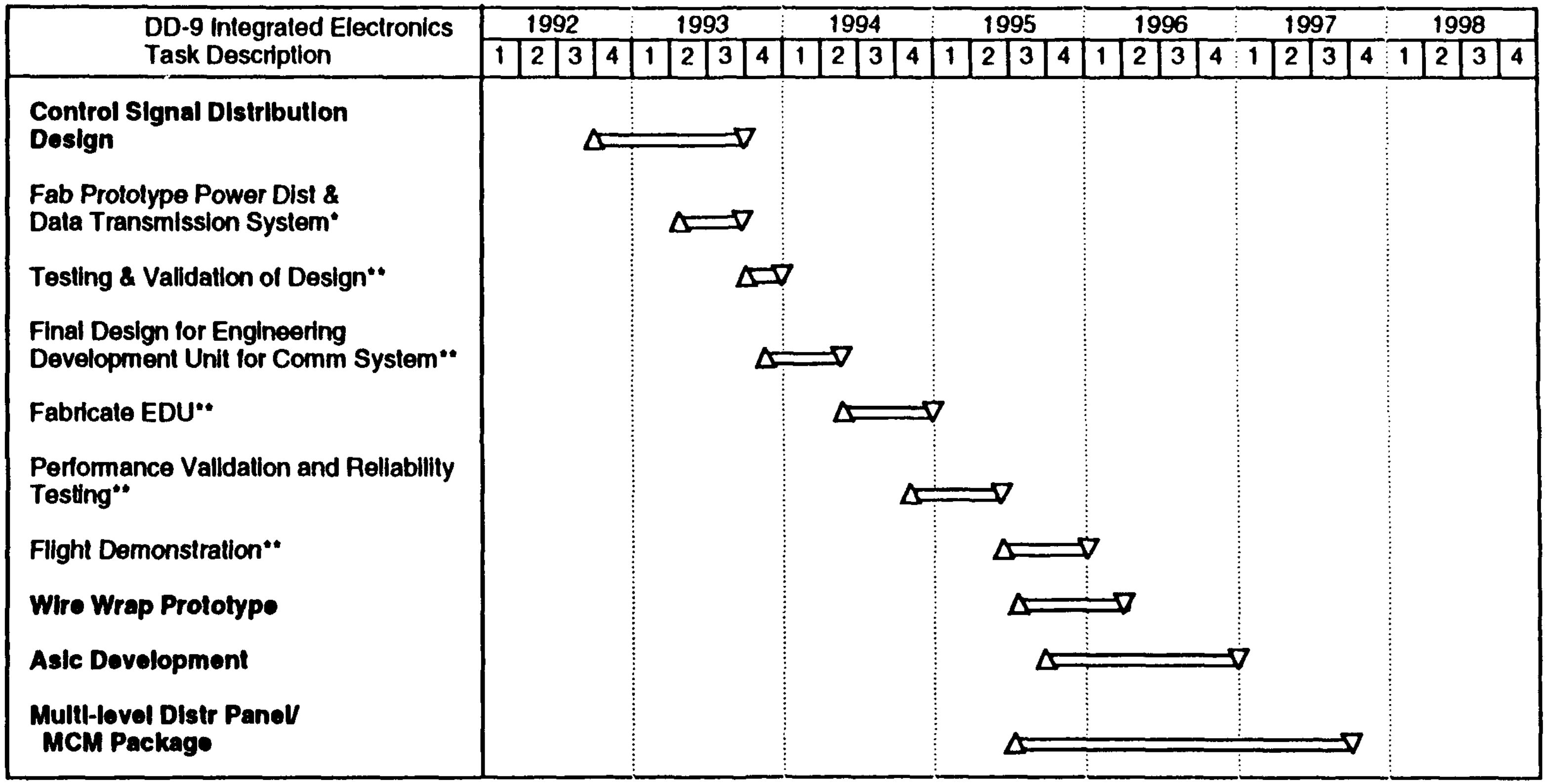


PROPOSAL BASIC/21 JANUARY 1993

ESM 21 JAN 93

Integrated Electronics

● DD-9 Overview Schedule with Development Effort



* - Supported by ONR Program N00014-92-C-0135/Dr. Steve Fishman Technical Monitor

**- Proposed Support by SDIO

Bold Items Are Martin Marietta Brilliant Pebbles Program DD-9 Effort

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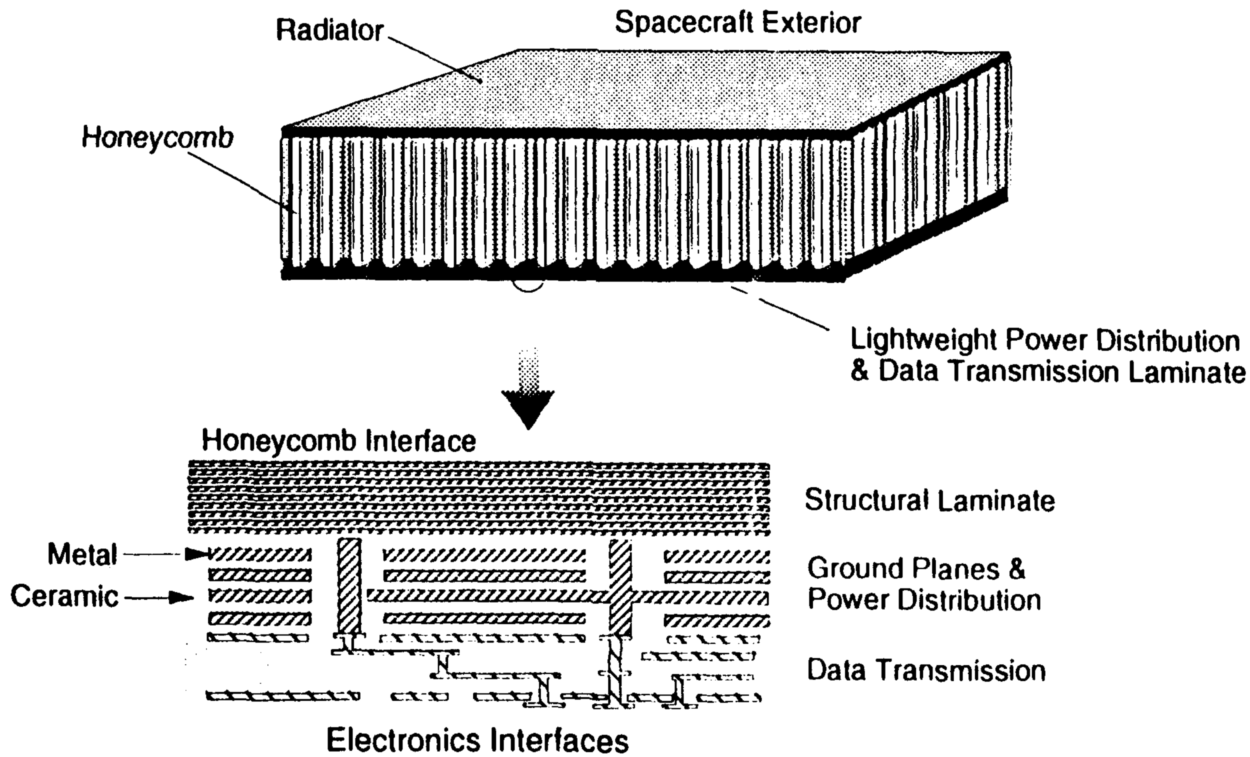
ASTRONAUTICS GROUP/MECHANICAL-R&T

150-9

Integrated Electronics Structure

- Incorporate Data & Power Planes into Skin Structure



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ASTRONAUTICS GROUP/MECHANICAL-R&T

150-8

DD 9 PRODUCTS

- Breadboard prototype electronics for LJRTTB integration.
- ASIC based I/ O for flight designs.
- Ultra-Light weight power and data distribution network.
- Space Qualification Tests
- Validation of design producibility.

Integrated System Damage Detection and Assessment

Mohan S. Misra
Martin Marietta , Mechanical R&T

MARTIN MARIETTA
Mechanical R&T

Integrated System Damage Detection and Assessment

Approach

- Incorporate Miniature Sensors and Advanced Multiplexing Technology into Spacecraft Structure

- Provide On-Demand Structure Health Status of Spacecraft to Predict
  - Lifetime for Intelligent Constellation Refurbishment
  - Accurate Assessment of Operation Environment for Future Design
  - Spacecraft and Subsystem Health Status

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Mechanical R&T

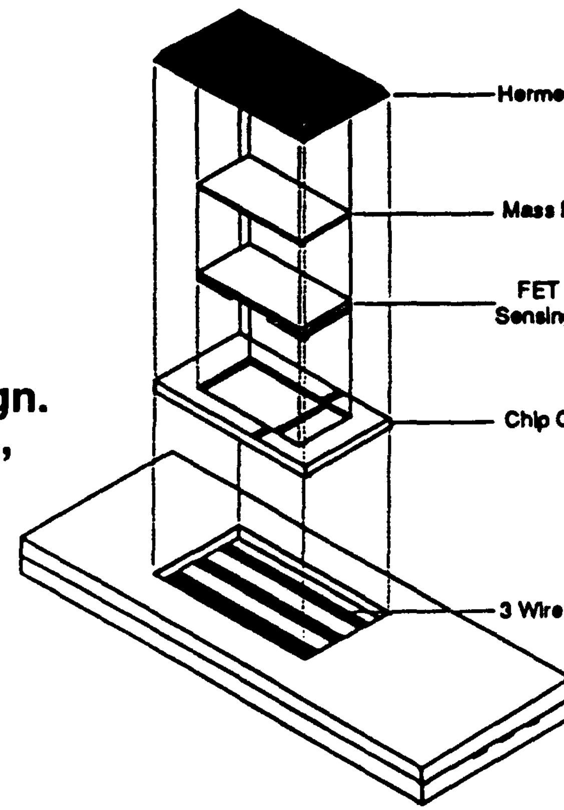
Integrated System Damage Detection and Assessment

Unique Health Monitoring Design:

- Multiplexed
  -Data Transmission For All Sensors Along Single 3 Wire Bus Embedded Within Composite

- Onboard Diagonistics and Data Regression
  - Reduces System Computational Requirements

- Same Fundamental Field Effect Transistor (FET) Design.
  – Miniature Load Cells, Accelerometers, Strain Gages, or Impact Sensors



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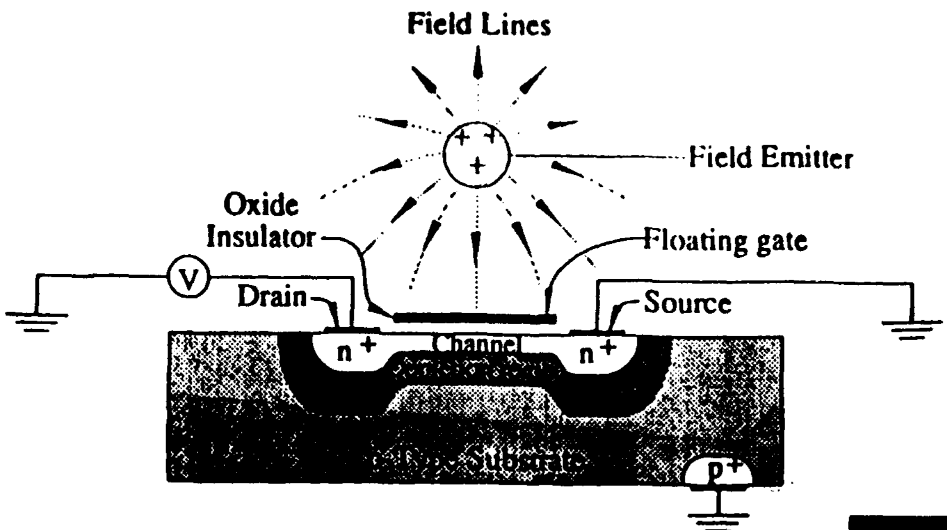
Integrated System Damage Detection and Assessment

Uni-Axial Strain Transducer (UAST)

- Cross-Section of Floating-Gate FET Electric Field Sensor With Electric Field Emitter
- Current Between Source and Drain is Related to the Charge Capacity Coupled onto the Gate
- Changing the FET-Emitter Spacing Allows the UAST to Be Calibrated for Displacement, Read Loads, Strains, Acceleration, etc.



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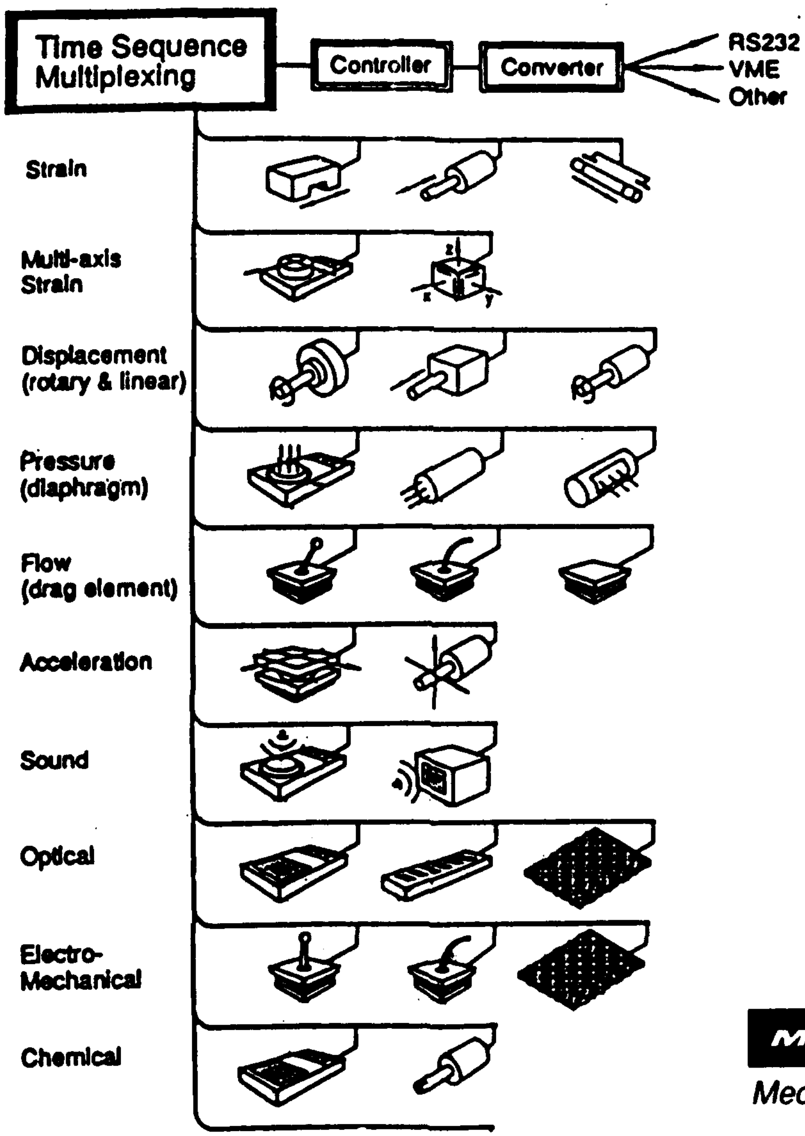
Integrated System Damage Detection and Assessment

Integrated Sensor Network



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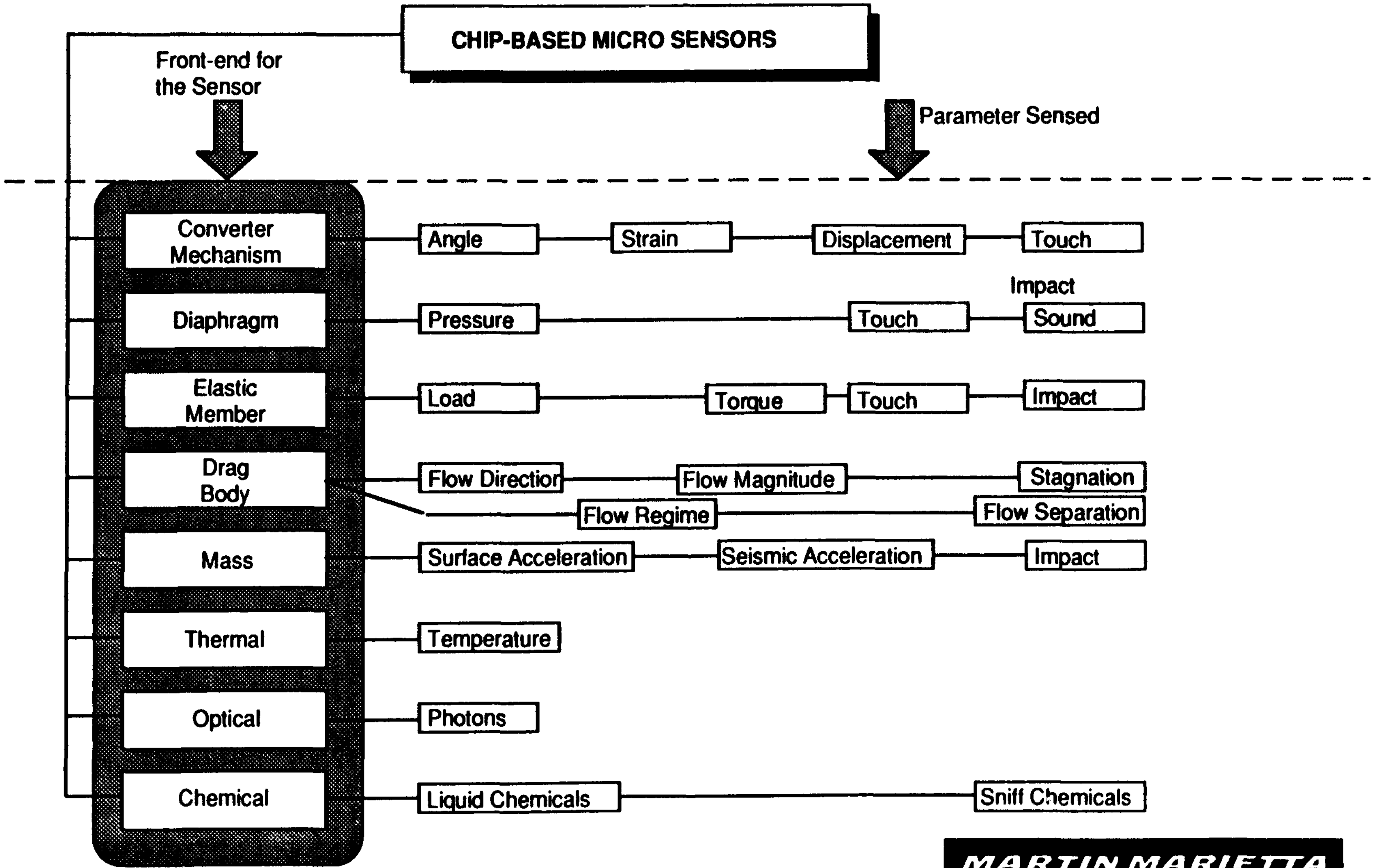
Integrated System Damage Detection and Assessment

Sensing Modalities Enable by Chip Based Micro-Displacement Sensors



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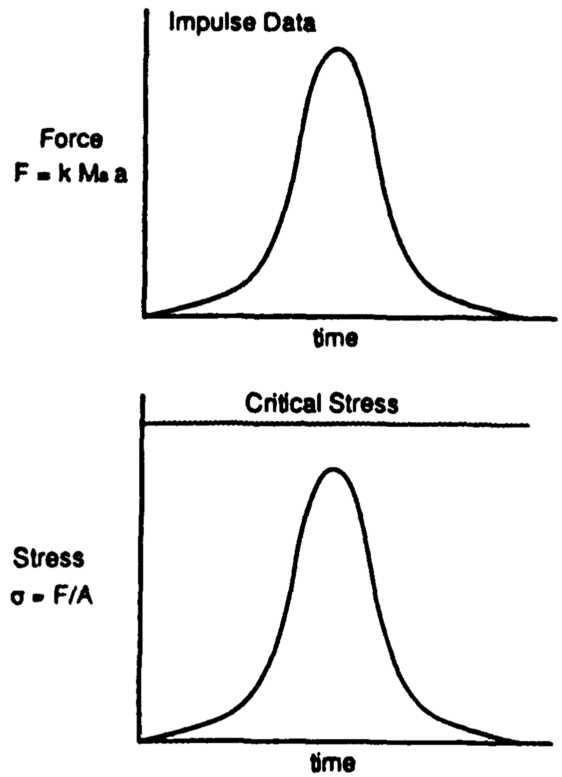
Integrated System Damage Detection and Assessment

Micrometeorite and Debris Identification

Technical Issues

- **Input**
  - Particle Impacting Surface of Spacecraft
- **Output**
  - Flaw Size
  - Impact Location
  - Impact Force
  - Strain Relaxation
- **Calculation**
  - Induced Stress
  - Shear Stress
  - Structural Degradation



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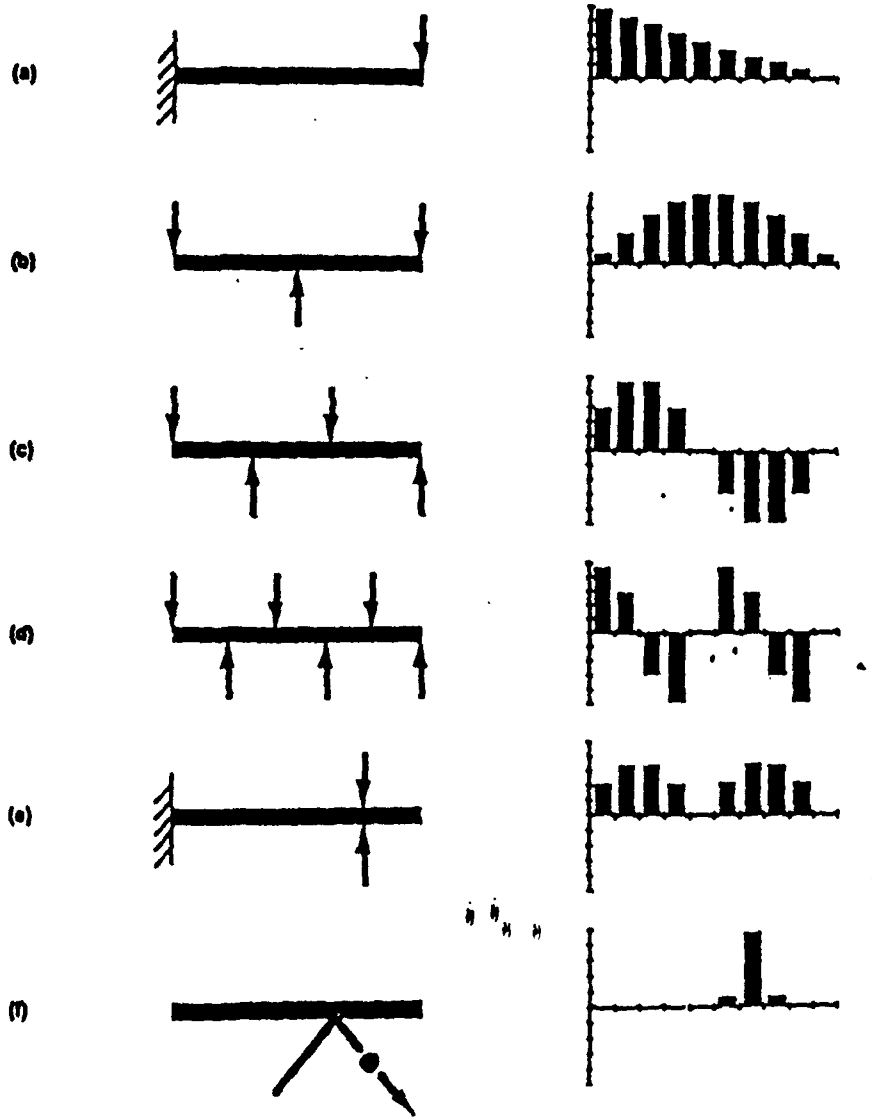
Micrometeorite And Debris Identification

Schematic Overview of Test Loading Patterns: (a-d) Multipoint Bending, (e) Frequency Domain Response And (f) Point Event Test



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8/12/92-BC-edb-1

Integrated System Damage Detection and Assessment

Micrometeorite and Debris Identification

Impact Sensing Technology
- Load, Strain, Acceleration, Acoustic, MEMS
- Multiplexed Array
- Integrated with Structural Composite

Instrumentation
- Particle Detection
  - Flaw Size
  - Event Location
  - Impact Energy

Damage Assessment
- Fracture Mechanics Model

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Integrated System Damage Detection and Assessment

Technical Approach

System Survey

- Establish Baseline Applications
- Survey Current Damage Detection Methods
- Identify Systems with High Potential Payoff
- Demonstration Article Concept Generation

Sensor Array Definition

- Impact Sensor(s)
  - Strain, Load, Acceleration, Acoustic
- Multiplexing Scheme
- Data Buss Specifications
- Power Requirements

Test Article Integration

- Design
  - Materials: Graphite/Polycyanate
  - Panel Size: 12-in. x 18-in.
  - Panel Stiffness
  - Array Size and Sensor Spacing
- Fabrication
  - Surface Mounted Sensors
  - Electrical Isolation of Data Buss and Sensors
  - Consolidation of Composite Panels
  - Integration of Data Buss
- Sensor Integration
  - Bonding of Sensors to Test Article
  - Electrical Interface Between Buss and Sensor

Data Acquisition and Analysis

- Data Transfer Software and Hardware Interface
- Impulse Data Collection
- Impact Position Calculation
- Damage Extent Calculation

Structural Integrity Modeling

- Fracture Mechanics Approach
- Confirmation of Model Prediction

Testing/Evaluation

- Verifacation of Sensor Operation
- Impact Loading Tests

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Mechanical R&T

INTEGRATED POWER APPROACHES

S. Rusty Sailors

The Aerospace Corporation

Phillips Laboratory

Kirtland, AFB, NM

IPP

(INTEGRATED POWER PANEL)

Current Boeing Development Contract

IAPT

(Integrated Advanced Power Technologies)

Proposed Concept

S.R. SAILORS
The Aerospace Corporation

INTEGRATED POWER PANEL

IPP

DESCRIPTION:

- Program That Combines Power Generation & Management Functions (Solar Cells, Shunt Controllers & Dissipators) on Solar Array Panels
- Removes Some Power Processing Functions From Spacecraft Bus and Relieves Thermal Management Concerns.
- Reduces Control & Cabling Requirements
- Highly Modular & Scalable
- Unique Solar Cell "Ramp" Interconnect Allows For Reduction In "Laydown" Costs & Simplifies Repair
- Inherent Fault Tolerance & Highly Redundant Design Allows For Leaving Some Number Of Failed Sections Intact Without Repair Or Significant Reduction In Performance
- Large Emphasis On Simplicity & Reduced Parts Count

S.R. SAILORS
The Aerospace Corporation

INTEGRATED POWER PANEL

IPP

SYSTEM BENEFITS:

- Reduces Spacecraft Buss Thermal Requirements & "Box" Count
- High Level Of Modularity Meets Multiple Mission Requirements
- Simplified Modules Reduce System Design & Recurring Costs
- Can Feed Primary Bus Or Supply Multiple Busses For Independent Systems
- Controller Design Meets High Level Radiation Requirements With Minimal Performance Impact
- Design Can Accept Newer Solar Cell Technologies When Available
- Program Emphasis On Low Number Of Part Numbers & Decreased Manufacturing Costs With Simplified & Inexpensive Testing

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The Aerospace Corporation

02/10/93

WORKSHOP ON ADVANCED SENSORY S/C STRUCTURES

INTEGRATED POWER PANEL

IPP

PROGRAM PLAN:

- Concept Exploration & Trade Studies Completed
- System Cost Benefits Studies In Process
- Significant Radiation Testing (Power Hybrids) Completed
- Preliminary Temperature Modelling Indicates Acceptable Profiles
- Repairability And Maintenance-For-Test Issues Under Trade
- Flight Demonstration Panel Definition & Specification In Process
- Component Procurement For Demo Panel Imminent
- Flight Demo Panel Ready Sep 94

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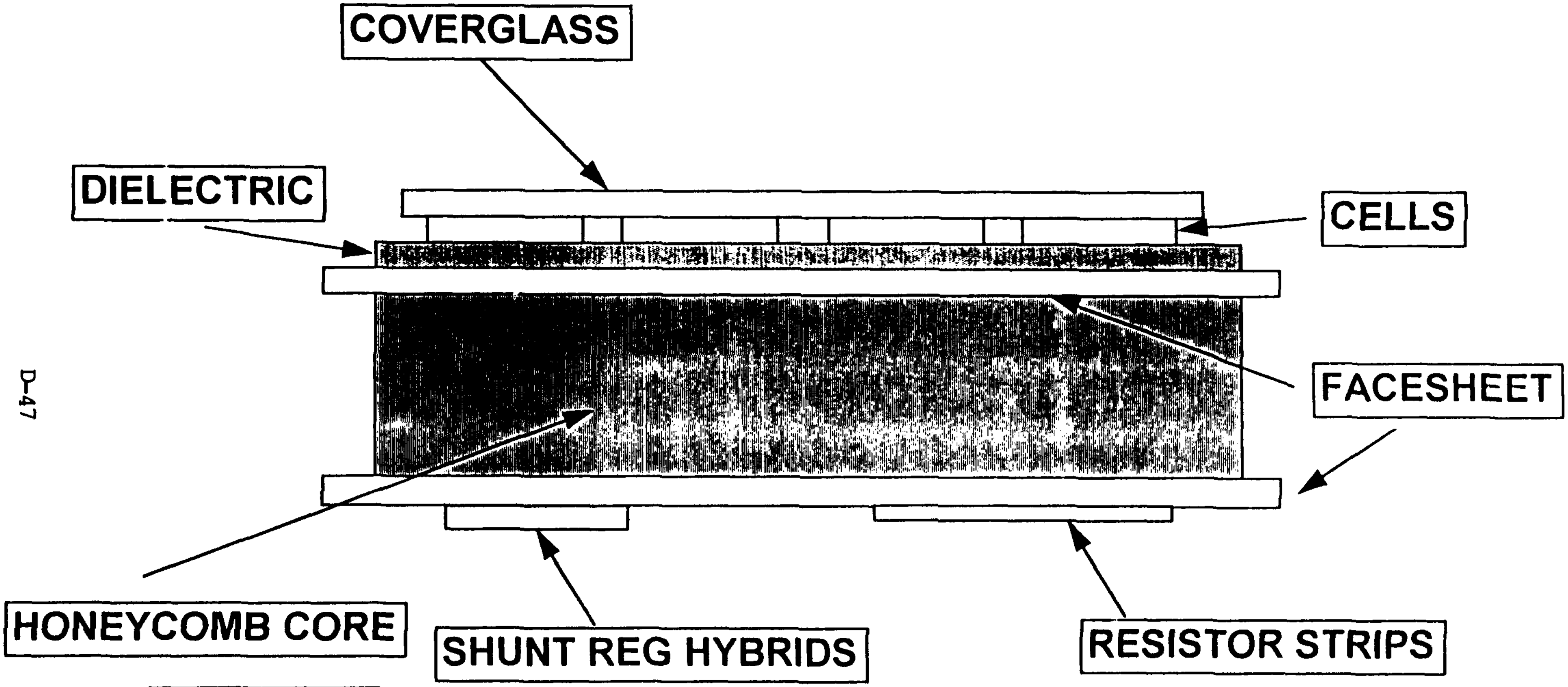
The Aerospace Corporation

02/10/93

BASELINE INTEGRATED POWER PANEL CONCEPT



CELLS: GaAs/Ge

COVERGLASS: CMG Microsheet w/ AR Coating

IPP BACKSIDE: Hybrid Drivers, Thermal Control, Resistor Strips

FACESHEET: Graphite Epoxy
HONEYCOMB CORE: Aluminum
DIELECTRIC: FM-73 Adhesive Film

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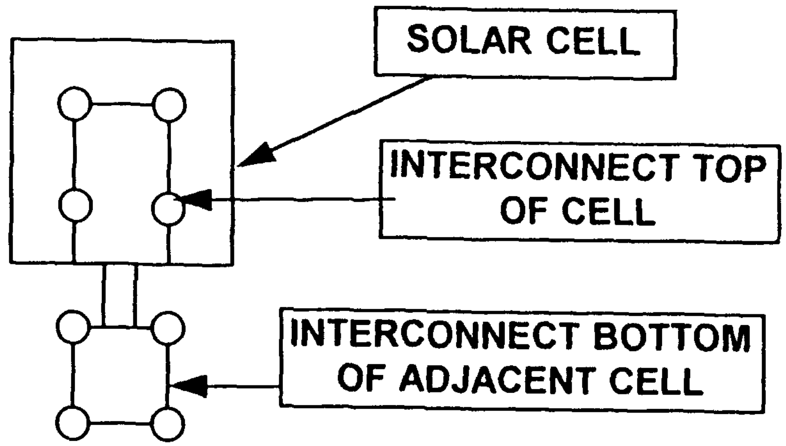
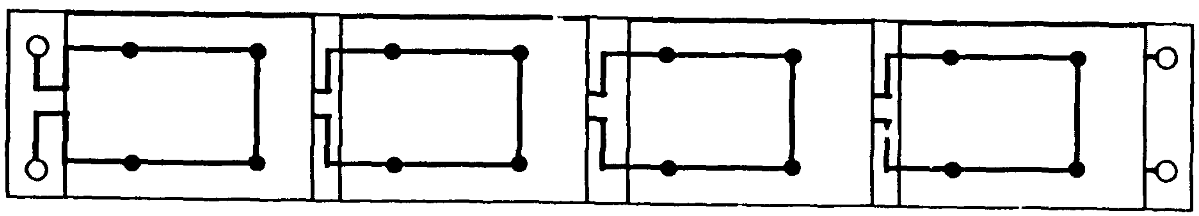
The Aerospace Corporation

02/10/93

IPP "RAMP" SOLAR CELL INTERCONNECT

UNIQUE CELL "RAMP" INTERCONNECT APPROACH REDUCES FABRICATION COSTS AND IMPROVES PERFORMANCE





GaAs/Ge CELL STRING WITH INTERCONNECTS

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The Aerospace Corporation

INTEGRATED ADVANCED POWER TECHNOLOGIES

IAPT

DESCRIPTION:

- Develop Highly Partitioned Power System Modules Utilizing Thin Film Technologies Integrating Power Generation, Power Conditioning & Energy Storage Functions Into A Singular Entity
- Approach Fully Integrates The Power Technology Programs Under Development By SDIO & The Phillips Laboratory

PROGRAM PLAN:

- Concept Exploration In Progress
- Cost benefits and Feasibility Studies Required

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The Aerospace Corporation

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INTEGRATED ADVANCED POWER TECHNOLOGIES

IAPT

SYSTEM BENEFITS:

- Power System Volume & Mass Reduction
- Significant Reduction in Recurring & Non-Recurring System Costs
- Fully Monolithic Approach Reduces Manufacturing Process Costs
- High Level of Modularity For Multiple Mission Applications
- Modular Interconnects For Power Bussing
- Simplified Autonomous Operation & Inherent Fault Tolerance
- Remote Power If Necessary
- Significant Commercial Value

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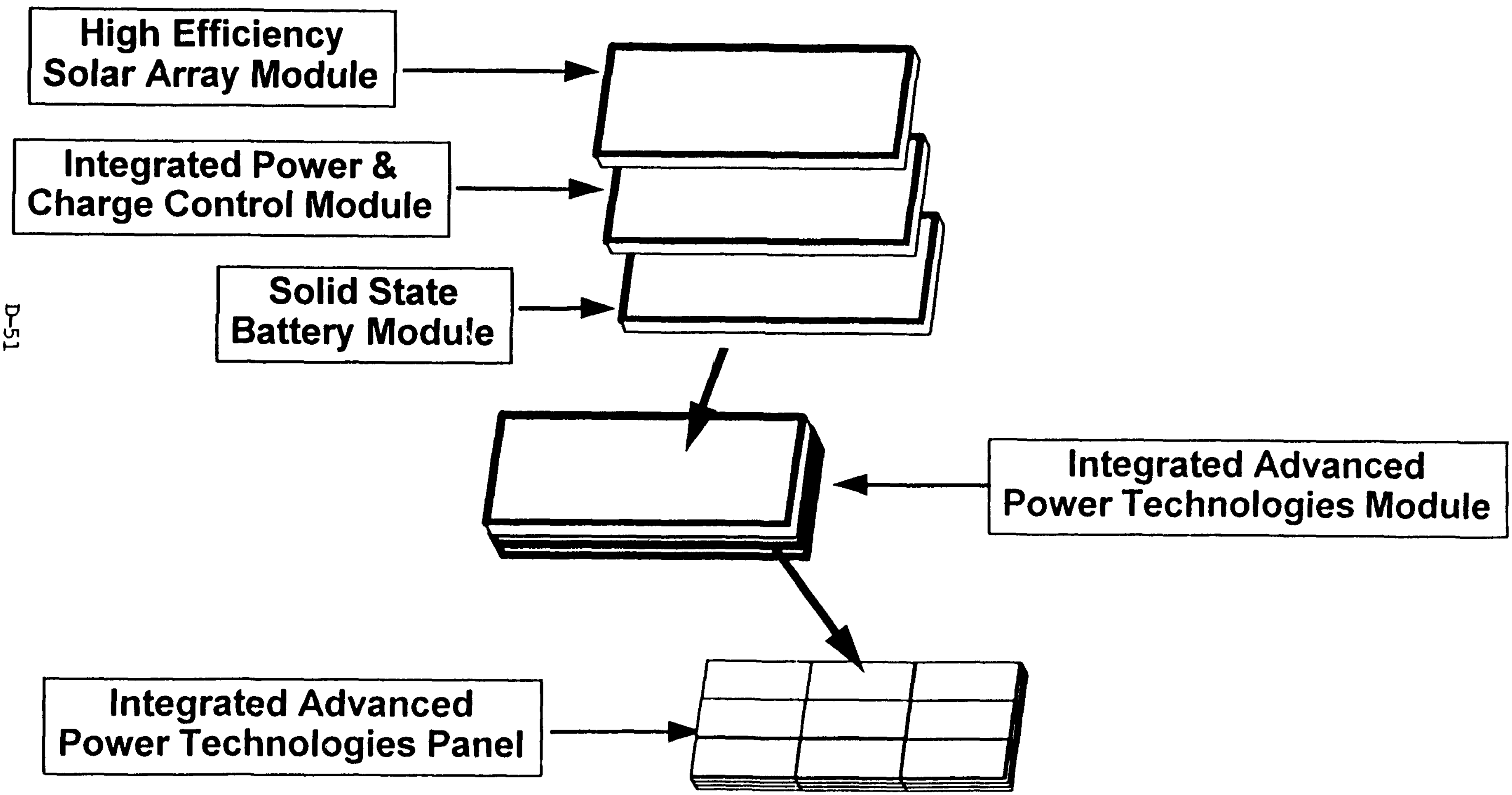
The Aerospace Corporation

WORKSHOP ON ADVANCED SENSORY S/C STRUCTURES

IAPT; MODULARITY APPROACH



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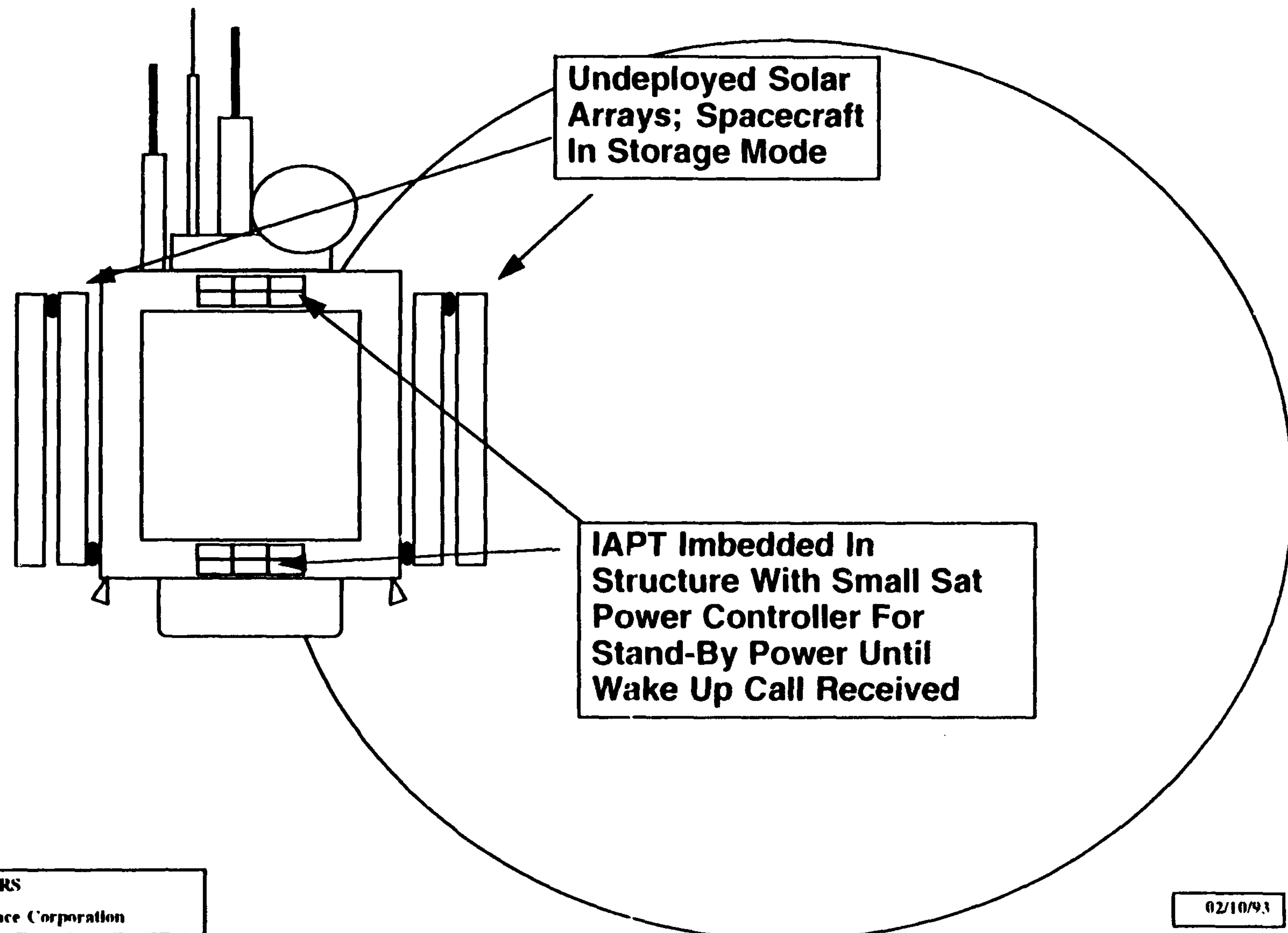
WORKSHOP ON ADVANCED SENSORY S/C STRUCTURES



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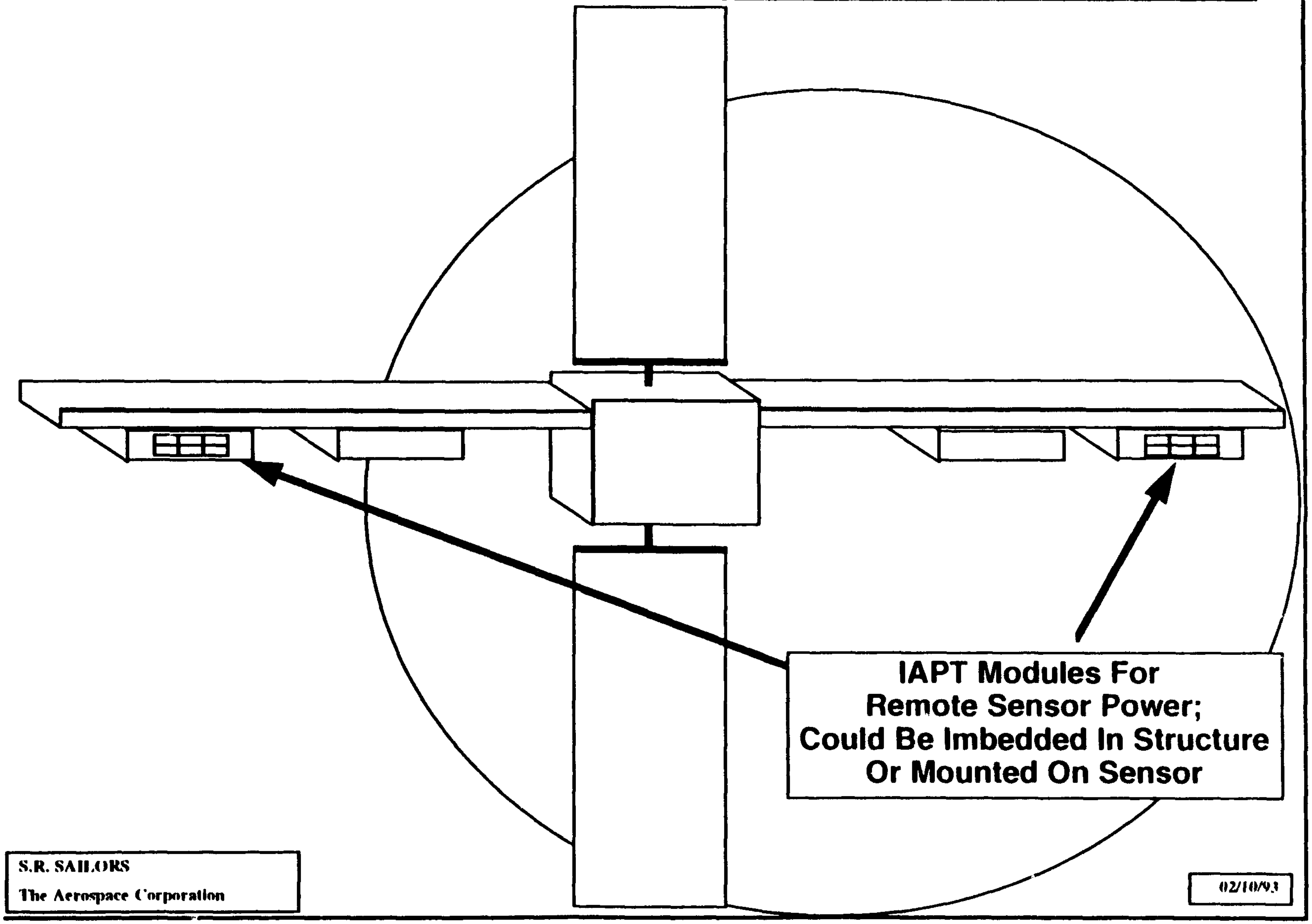
WORKSHOP ON ADVANCED SENSORY S/C STRUCTURES



S.R. SAILORS
The Aerospace Corporation

02/10/93

Structurally Integrated Sensor Technology

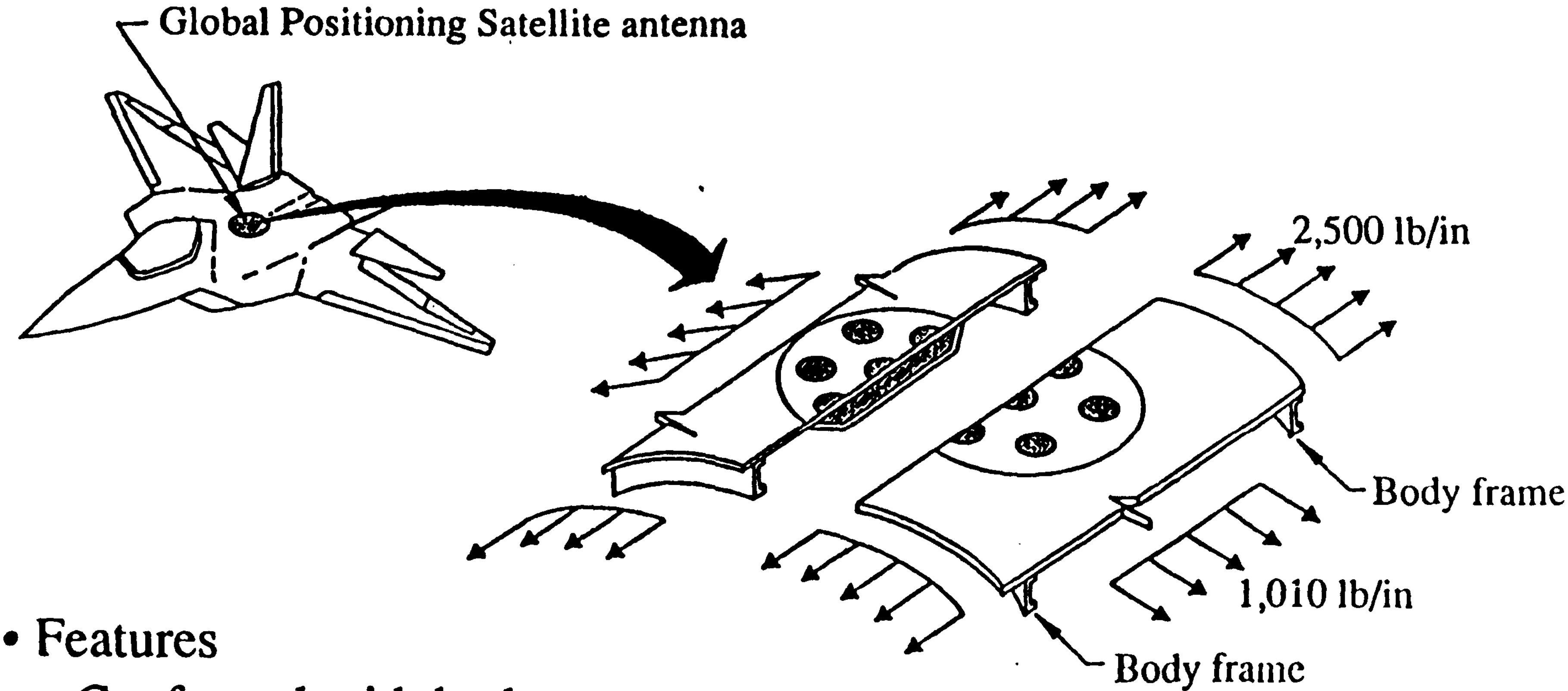
Presented by:
Dr. Roy Ikegami
Boeing Defense & Space Group

Presented at:
Workshop on Advanced Sensory Spacecraft
Institute for Defense Analysis
Alexandria, VA

February 10, 1993

9551-4 .bm-n 93423.1

Load Bearing Structurally Integrated Apertures - Conformal Antenna

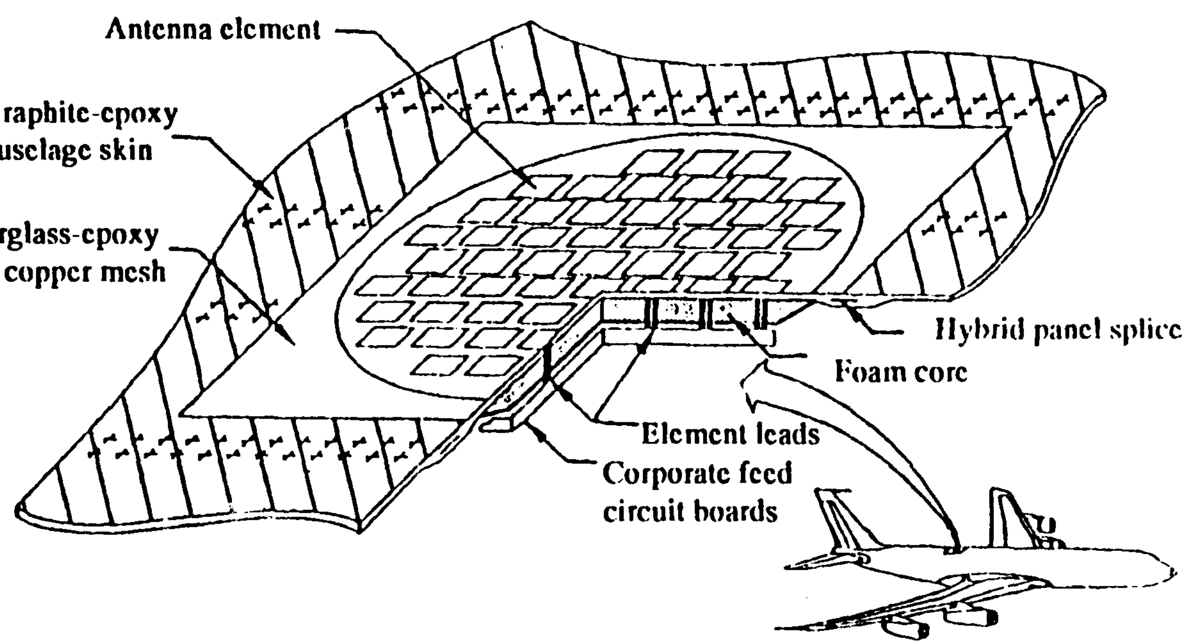


- Features
  - Conformal with body contour
  - Antenna panel to match strength and stiffness of surrounding skin
  - Structural integration techniques
    - Structural splice
    - Mechanical fasteners

Boeing Defense & Space Group

Conformal Load Bearing Phased Array

GPS Technology Demonstrator Concept

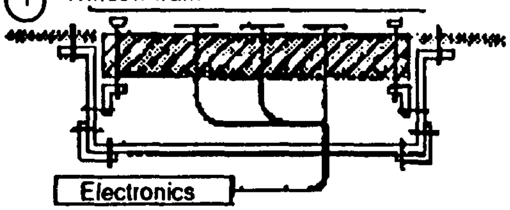
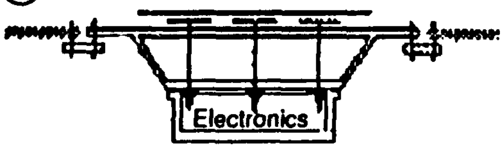
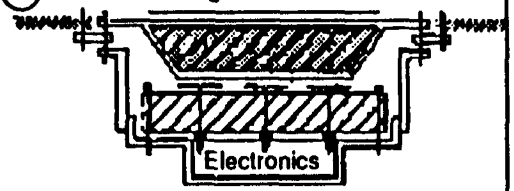
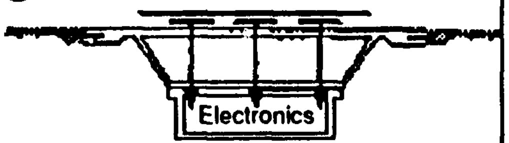
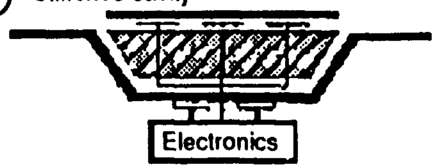


Issues

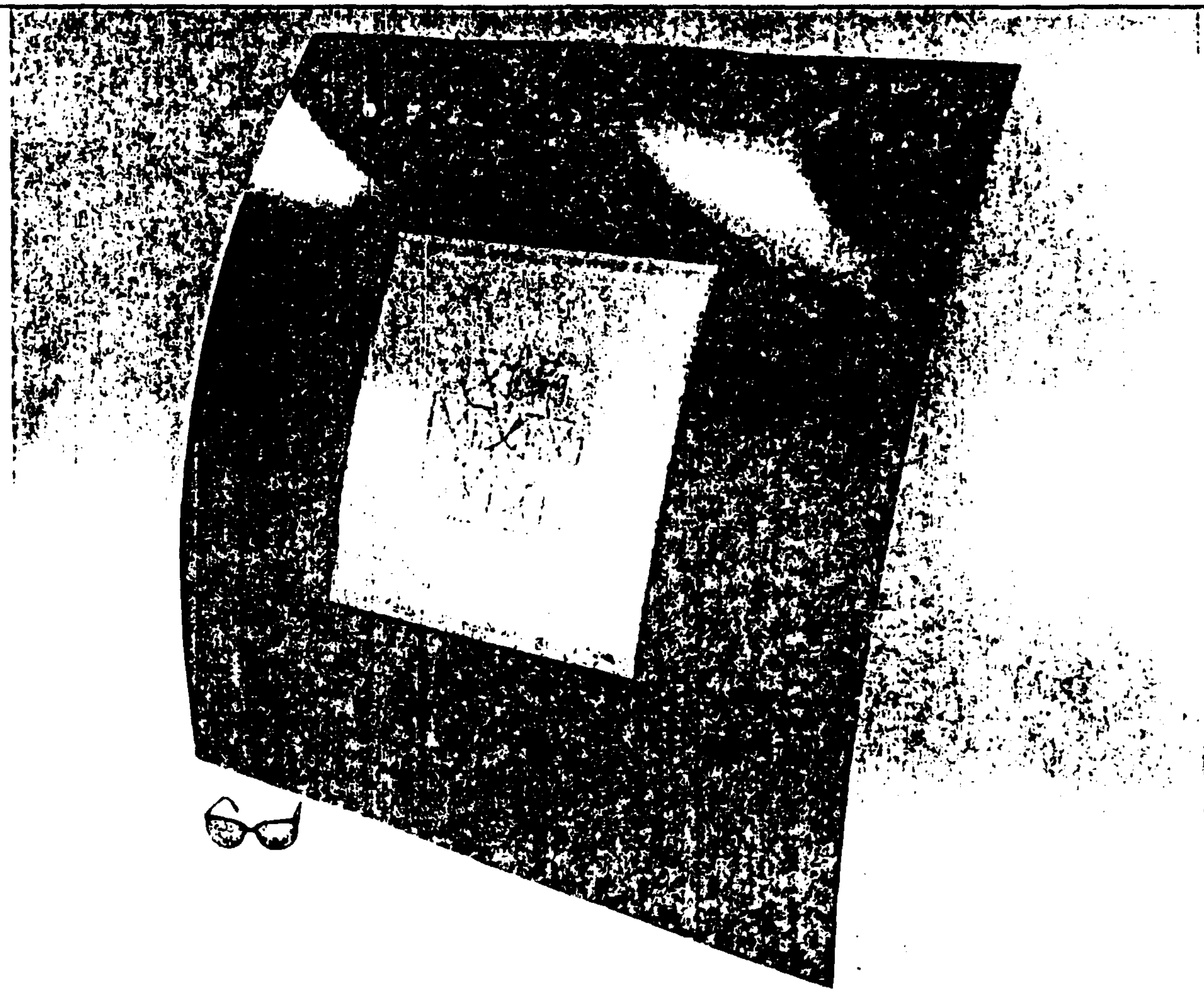
- Strength/stiffness/durability
- Reliability/supportability
- EMI protection
- RF distortion at higher frequencies due to structure deformation

Boeing
Defense &
Space Group
Engineering

Structurally Integrated Apertures - Array/Structure Integration Concepts

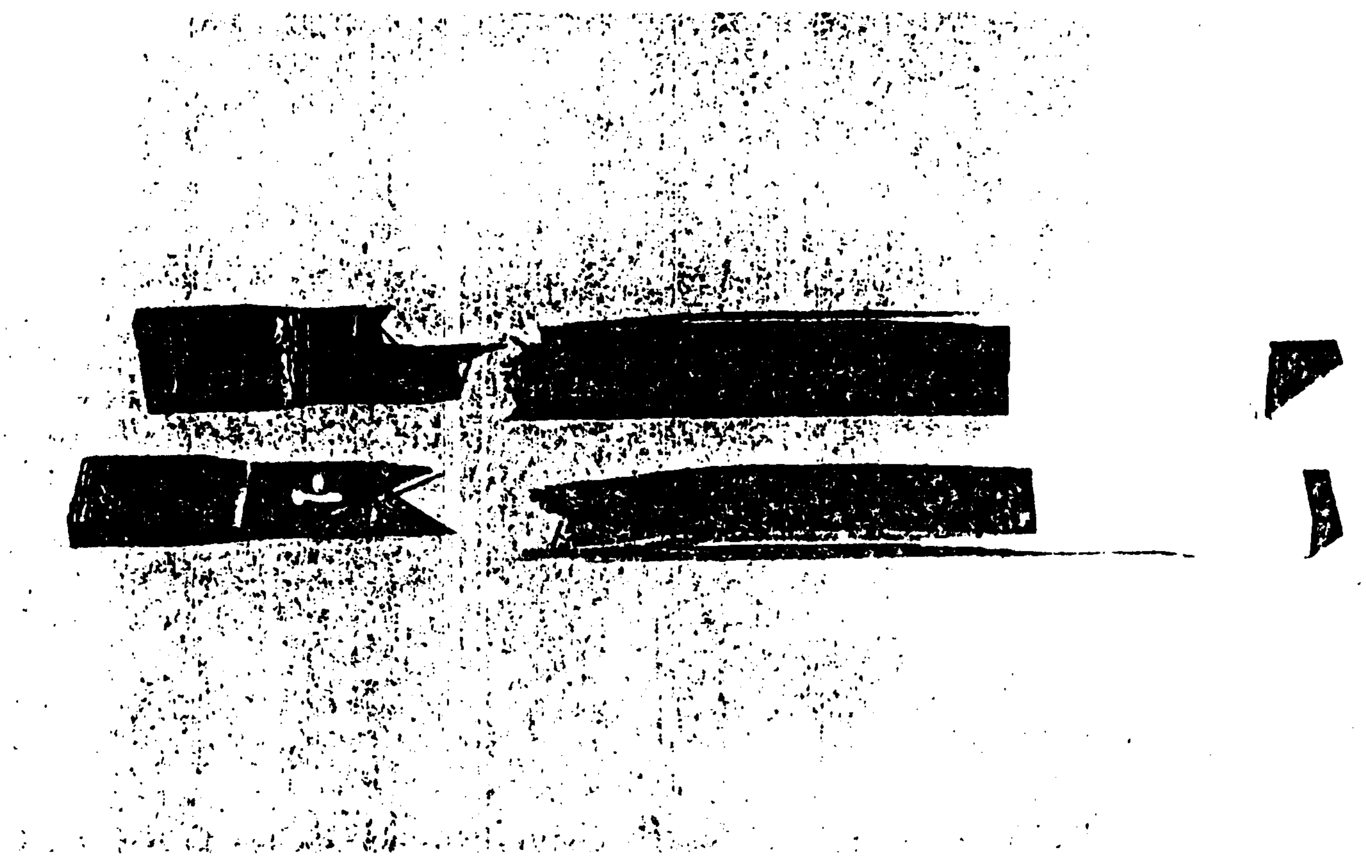
Concept	Description	Comments
(1) Window frame 	• Environmental cover • Window frame structure • Antenna panel attached via strain isolating tabs • Pressure containment panel additional • Distant electronics • Load bypass antenna	• Today's method • Item replaceable • Greatest weight design • Greatest volume design • Insensitive to flight strain
(2) Mechanically fastened dielectric window 	• Environmental cover • Sandwich panel structure • Conformal • Load traverses antenna panel • Panel performs pressure containment • Electronics local	• Innovative • Item replaceable • Reduced weight • Least volume • Flight strain sensitive
(3) Nonload bearing window 	• Dielectric sandwich panel reacts loads • Sandwich panel contains pressure • Conformal • Antenna looks through sandwich	• Not innovative • Item replaceable • Restricted antenna aperture • Avionics isolated from flight strain • Greatest volume design
(4) Spliced dielectric window 	• Same as (2) except for splice attachment into composite skin	• Innovative • Item replacable • Structural panel • Least weight • Least volume • Avionics insensitive to flight strain
(5) Stiffened cavity 	• Environmental cover • Concave skin/stiffened structure • Antenna panel attached via strain isolating mounts • Continuous skin contains pressure • Conformal • Electronics local	• Innovative • Reduced weight • Reduced volume • Avionics insensitive to flight strain • Poor load path

Structurally Integrated Antenna Panel



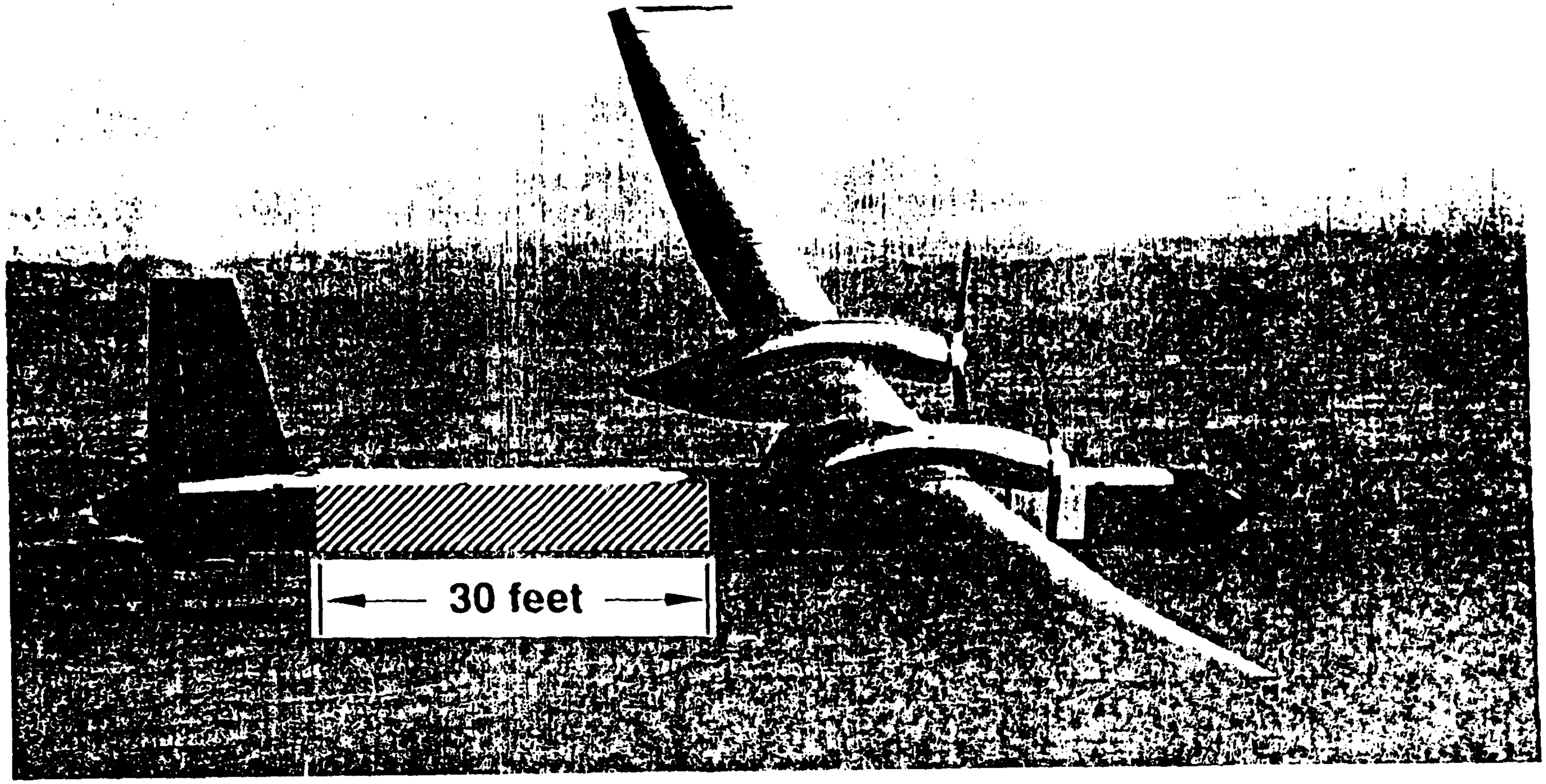
corporate.md 12

Hybrid Splice Integration



Achieved 117% of ultimate load for room temperature test condition

Benefits of Load Bearing Antenna



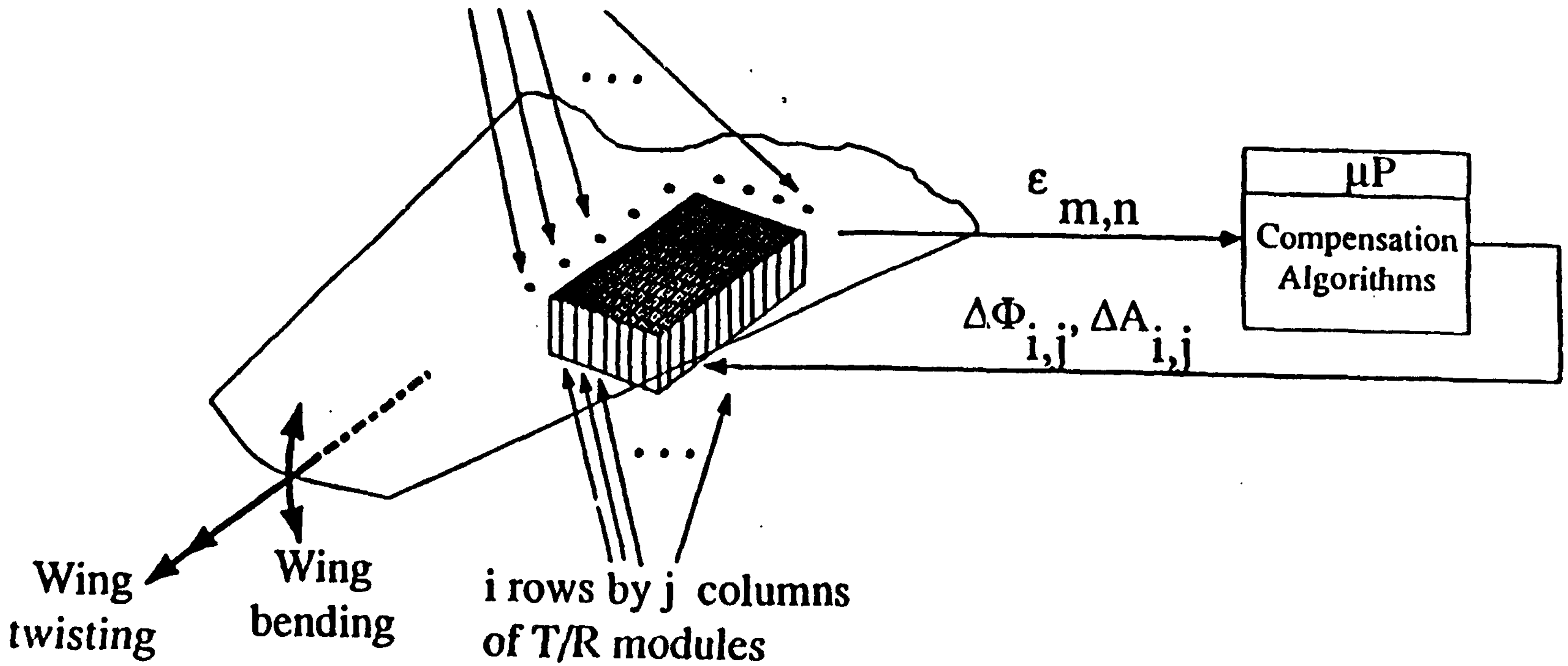
61% lighter than best vendor design

corporate md 21

Structurally Integrated Aperture Characteristics

Challenge #	
1	Individual elements move
2	Are physically stressed
3	Are heat sources
4	Are truly conformal (double or compound curves)
5a	May point the wrong way
5b	Have conformation and material which are not under control of structures designer-but is a part of his design
6	Shall not interfere with A/C integrity and durability
7	Producibility/supportability is not as good as the current non-embedded T/R; life time must be much greater

Concept for Compensating Structural Deflections of Wing Array



- Compensation algorithms
  - Interpolate i x j deflections from m x n strain measurements
  - Compute $\Delta\Phi$ and ΔA commands for i x j T/R modules

Structurally Integrated Apertures - Enabling Technologies

Structural:

- Load bearing dielectric window integration
  - Structural design concepts splicing/joining versus mechanical fasteners
  - Window materials design allowables
  - Strength, stiffness, durability of windows and joints/splices
  - Residual stresses
  - Overall dielectric properties

- Sensors to detect antenna array structural deformations
  - Fiber optic strain sensors
  - Algorithms to transform strain to deformations
  - Algorithms to electronically correct phase/amplitude errors

- Electronic module and manifold integrations
  - Reliability and maintainability
  - Structural cooling

Boeing
Defense &
Space Group

Structurally Integrated Apertures
The Next Step

Issue	Action
• Sensor development	• Encourage sensor industry • Encourage materials suppliers
• Integration	• Embedment vs. attachment trade studies • Laboratory tests
• Reliability/supportability/ producability	• Move Avionics towards high MTBF • Include Logistics and Manufacturing support functions in system concept development
• Structural integrity	• Fatigue and failure analysis • Trades on sensor size and degree of embedment • Combined component level structural and RF performance tests

Move Towards System Demonstration

95514 abm ri 93423 3

Microsensors and Microinstruments

T. VanZandt, W. J. Kaiser, T. W. Kenny, J. K. Reynolds, H. K. Rockstad, M. E. Hoenk, L. Miller, R. Stalder, W. B. Banerdt, D. Crisp, E. Vote, J. Podosek, M. H. Hecht

Center for Space Microelectronic Technology
Jet Propulsion Laboratory
Pasadena, CA

Motivation

In Situ Science--Present Sensors have Mass, Power, Size Requirements that are Incompatible with Many Applications (Earth and Space)

Miniaturization of Instruments Crucial to Expanding Applications Important to Retain Same Performance

Microfabrication Techniques Alone Do Not Enable This

New Measurement Principles are Needed

Development of New Principles is Focus

JPL Invented Position Sensing Technologies

One Dimensional:

Tunnel Sensor

Electron Tunneling--Revolutionary Microsensor

10^{-14} m/(Hz)$^{1/2}$ Position Sensitivity

Ideal For AC Applications (Above 1 Hz)

High Frequency Capacitive Position Sensor

<10^{-13} m/(Hz)$^{1/2}$ Position Sensitivity

Ideal for Broadband Applications (DC to 100 kHz)

Multi-Dimensional:

Capacitive Based Edge Sensors

Precise Measurement of Relative Displacements and Rotations of Structures

Applications of Position Transducers

Tunnel Sensor -Based Broadband Uncooled Infrared Detector
  Golay Cell

Tunnel Sensor-Based Accelerometers
  Hydrophones, Vibration Monitoring

Tunnel Sensor-Based Magnetometer

Broadband Capacitive Accelerometer
  Seismometer, Microgravity Accelerometer, Orbital Diagnostics

Capacitive Pressure Sensor
  High Sensitivity Applications: Meteorological Package

Capacitive Multi-Electrode Sensor
  Active Control for Multi-Component Mirrors

JPL Microinstrument Development Program

Tunnel Sensor Program

Microaccelerometer/Microseismometer
- Martian Network, Microgravity, Orbital Diagnostics

Microweather Station
- Pressure, Temperature, Humidity, Wind, Aerosol
- Application on Martian Surface Network and Earth's Atmosphere

Adaptive Optics
- Micromachined Deformable Mirrors for Active Figure Control

Binary Optical Elements
- Miniature Electron Beam Defined Imaging and Dispersive Elements

Miniature Analytical Instrumentation
- Micromachined Charged Particle Energy/Mass Analyzers

Objectives of Workshop

1. Identify Technical Issues for Spacecraft Sensory Structures

Need to Develop Microsensors for Use In Constrained Applications
High Performance (**Sensitivity**) Microsensors are Critical: Enabling Technology

Not Off-the-Shelf Technology
Research into Fundamental Measurement Techniques is Important

2. Assess the Viability of Initiating Research Efforts in Space Sensory Structures

Strong Need to Be Applications Oriented

3. Determine Steps in Technology Development
"Sensory" Structures: Sensors are Crucial
Bottom-Up Approach

I. Sensors Should Be Emphasized First

  a. Determine What Is to Be Sensed

  b. Is it Physically Possible/Practicable ?

  c. If so, are Appropriate Sensors Available?

  d. If Not, Directed Research Into Physical Possibility

  e. If Promising, Develop It

II. System Engineering and Integration

4. Suggest Near and Far Term Applications

JPL Could Benefit From This Approach

Mars Environmental Survey (MESUR) 80 kg Lander, 10 kg Science

1999 Tentative Launch

Increased System Integration Could Greatly Improve Science Return

For $500M to $1000M Mission

Discovery Class Missions ($150M)

Venus, Pluto, Martian Poles, etc.

TRW

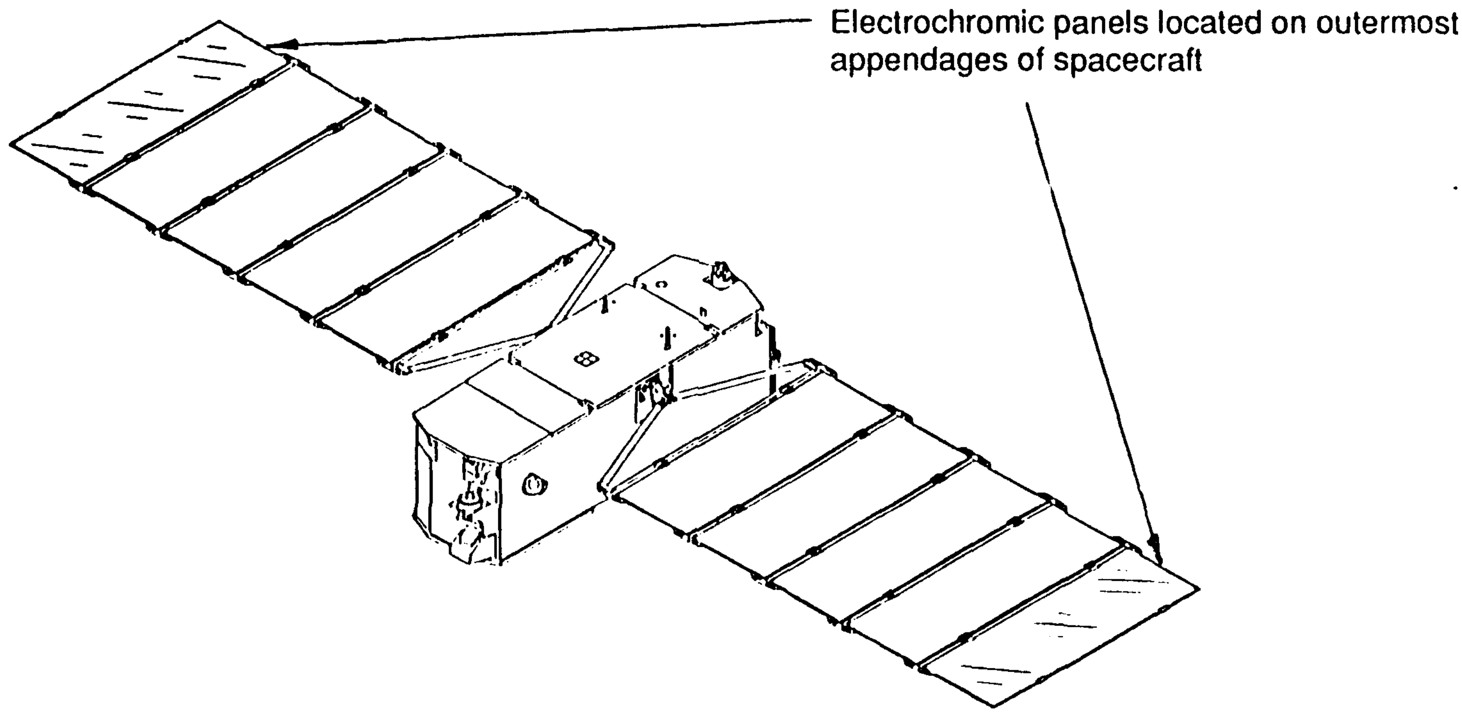
New Design Technologies

Ted Nye
10 February 1993

1. Electrochromic Sail
2. Hairy VEM
3. Piezoceramic Shaping
4. Smart Healing Structures

1. Electrochromic Sail

- Use electrochromic material on a panel to perform satellite steering via solar pressure



1. Electrochromic Sail

- Electrochromic devices change their light transmission, absorption, and reflection characteristics based on the application of electric potentials (smart window)
- Low cost, simple design, no moving parts
- Approximate 1-2 square meter panel needed to steer a BP
- Very low power (~1 watt), low voltage (~1.2 V), lightweight
- Panel electrically acts like a capacitor, needs to be pumped up approximately every 24 hours
- Competing technologies are magnetic torque rods (more complex), wheel momentum devices (much more complex), and propulsion systems (most complex)

1. Electrochromic Sail

Design Status:

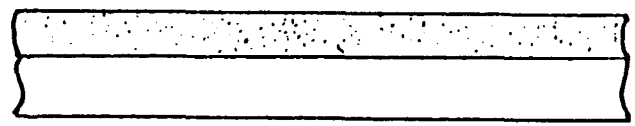
- Concept has been environmentally tested for
  - Temperature
  - UV Exposure
  - Radiation Exposure
  - Electrical/optical Behavior

- Concept is good contender for a flight experiment

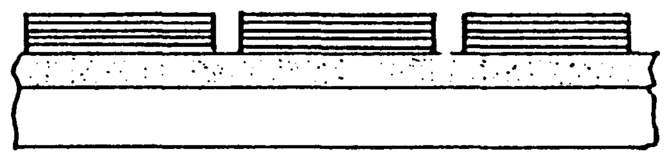
2. Hairy VEM

- Viscoelastic material with embedded chopped fibers that act as a pseudo constrained layer
- Eliminates conventional constrained layer and load transfer techniques

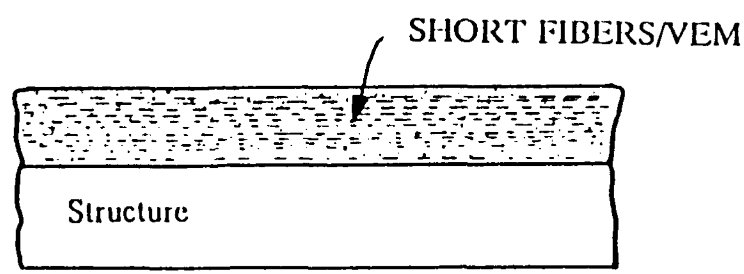
Pure VEM Treatment



Constrained Layer Treatment

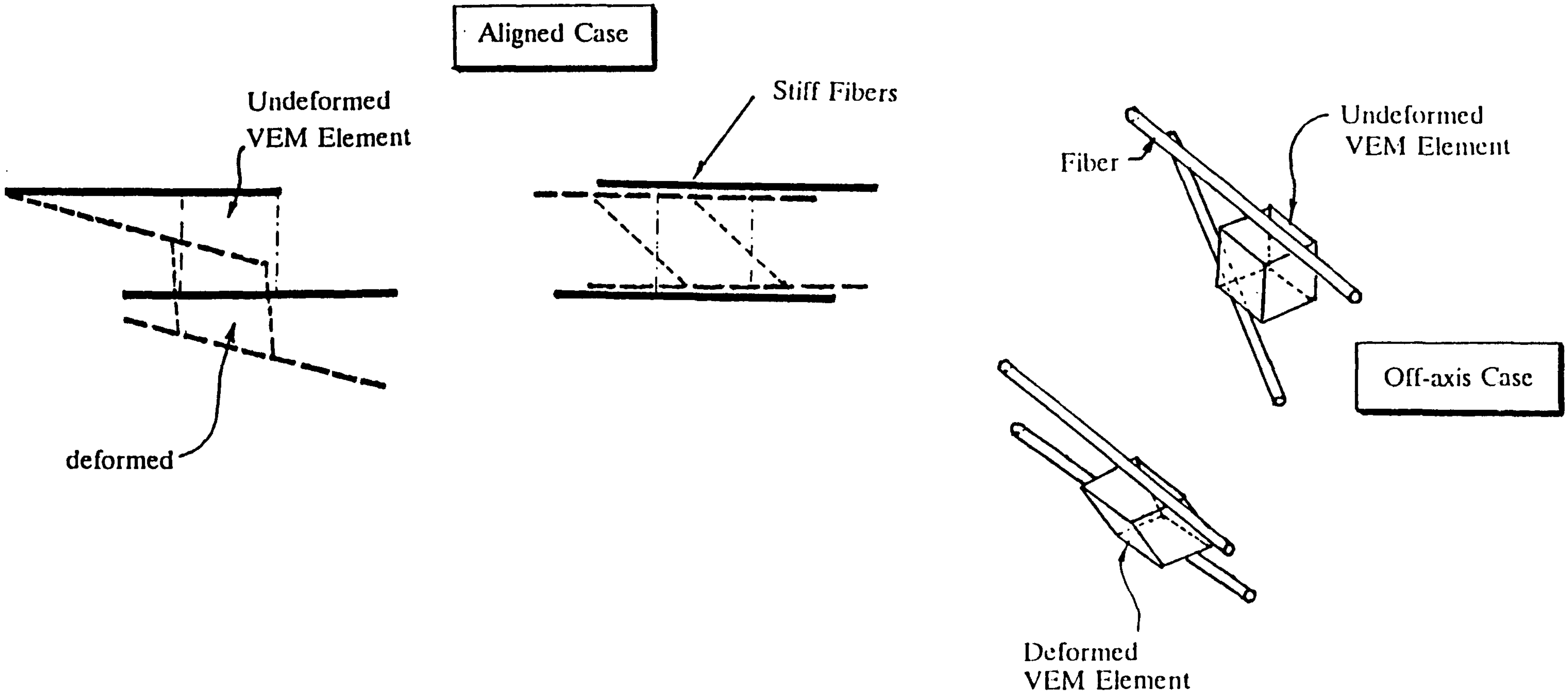


Hairy VEM Treatment



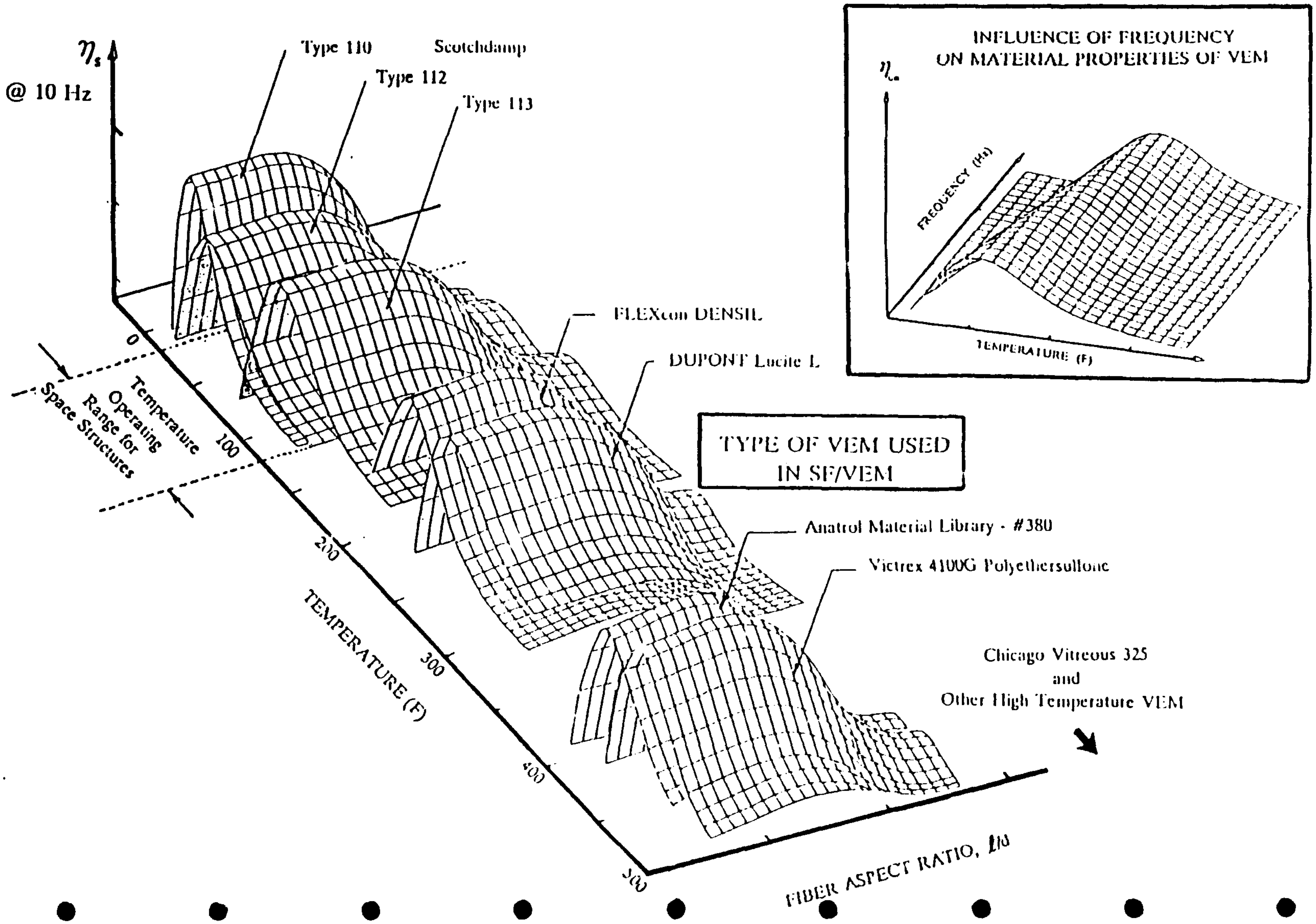
2. Hairy VEM

- Shearing deformation of VEM is induced by fiber interaction
  - More efficient load transfer to the VEM
  - Enhanced energy dissipation through fiber interaction



2. Hairy VEM

Damping as a function of Temperature and Fiber Aspect Ratio



2. Hairy VEM

Design Status:

- Preliminary parameter optimization has been completed (fiber length, VEM stiffness ratio, fiber volume fraction, fiber arrangement, type of VEM used)

- Material has been prototype fabricated and tested

- Mass production manufacturing method remains to be developed

3. Piezoceramic Shaping

- Current limitations in available ceramic piezoelectric wafers cause expensive work around solutions and lost performance

- Limitations include:

  Available Thickness - Less than 5 mils is desirable
  Available Shape - Flat wafers only, physical limits to curvatures that can be created
  Material Aging - Properties are lost exponentially with time
  Poling Direction - Desirable to pole PZT along length rather than thickness

- Current smart structures are being built within these contraints

4. Smart Healing Structures

- Use smart struts to detect, locate, and fix structural faults

- Structural faults will change resonant frequencies and damping

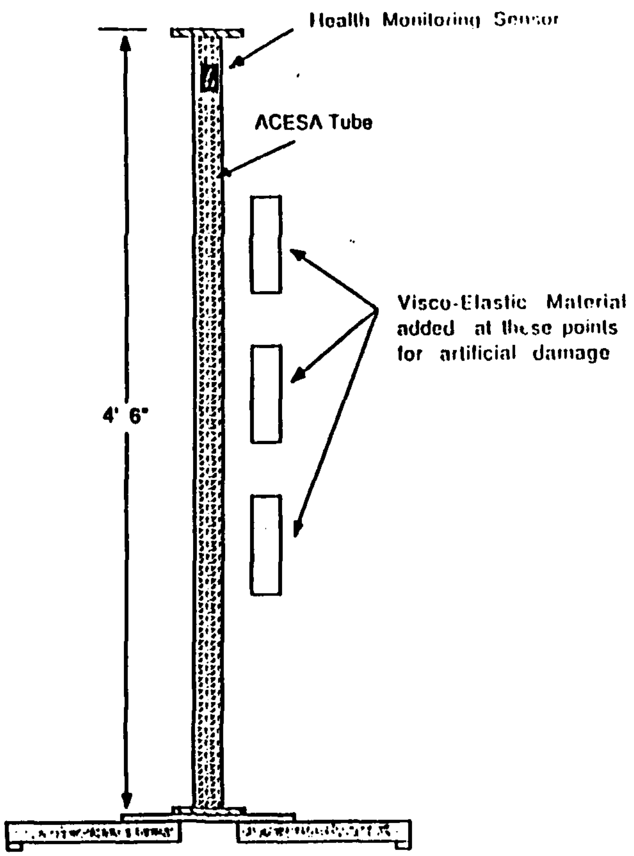
  Stiffness degradations -Resonant frequency changes
  Delaminations - Damping increases
  Loose joints - Poor coherence transfer functions

- Embedded piezoceramics can provide "muscle" action to bleed internal unmixed epoxies into structural faults

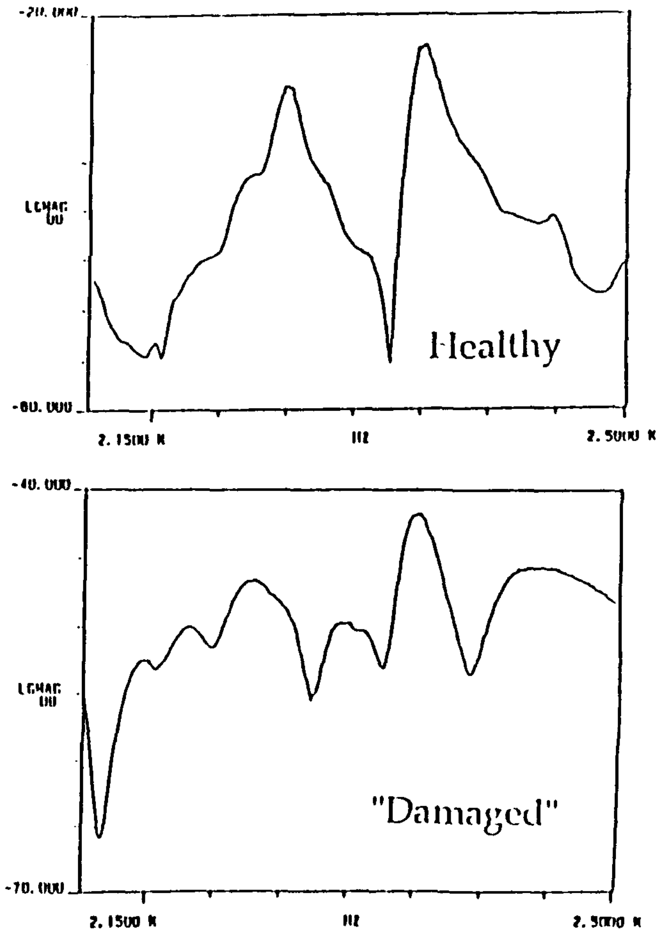
  PZTs can excite local areas to provide part A and Part B mixing
  Later system id can assess strength status of the repair

4. Smart Healing Structures

- ACESA health monitoring demo showed "damage" could be detected and located used lost modal strain energy techniques

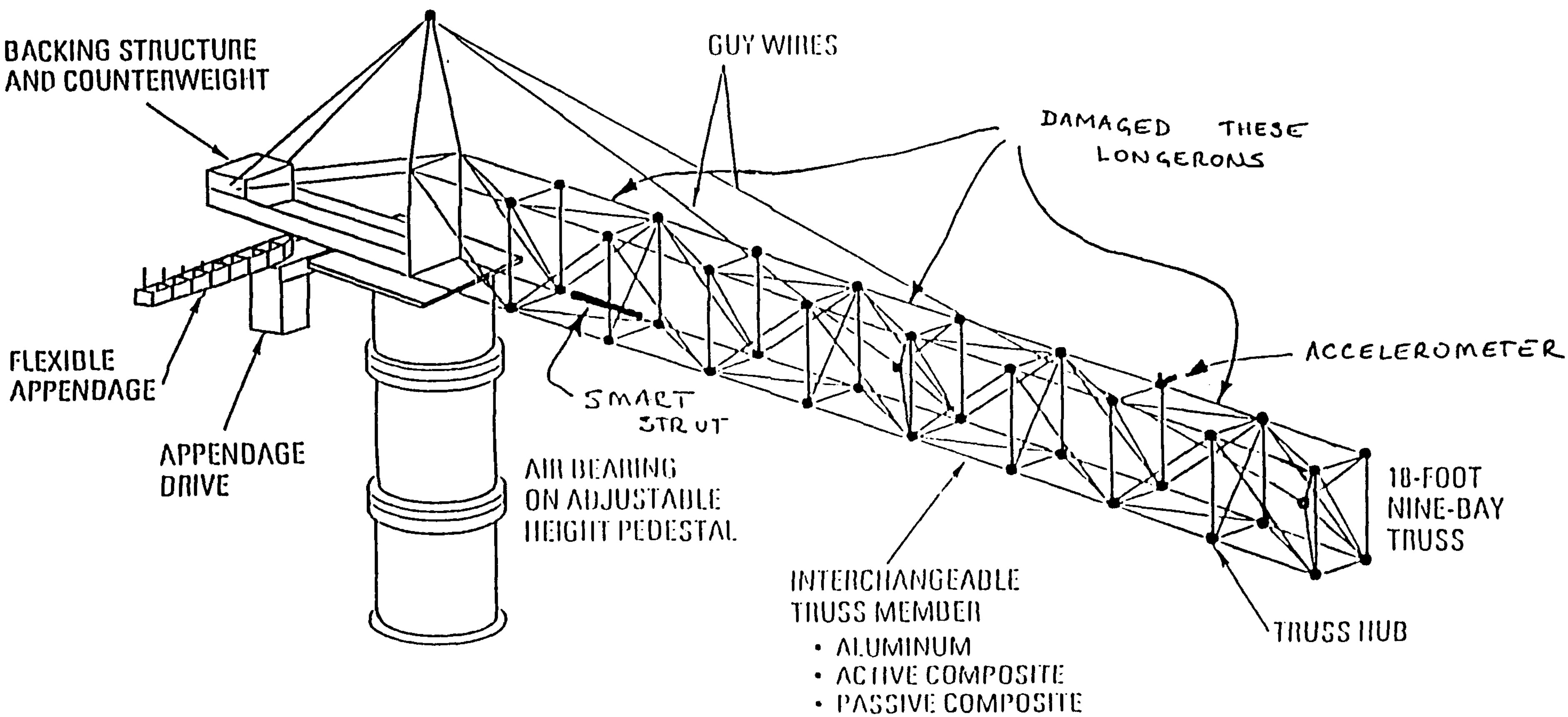


Test Setup



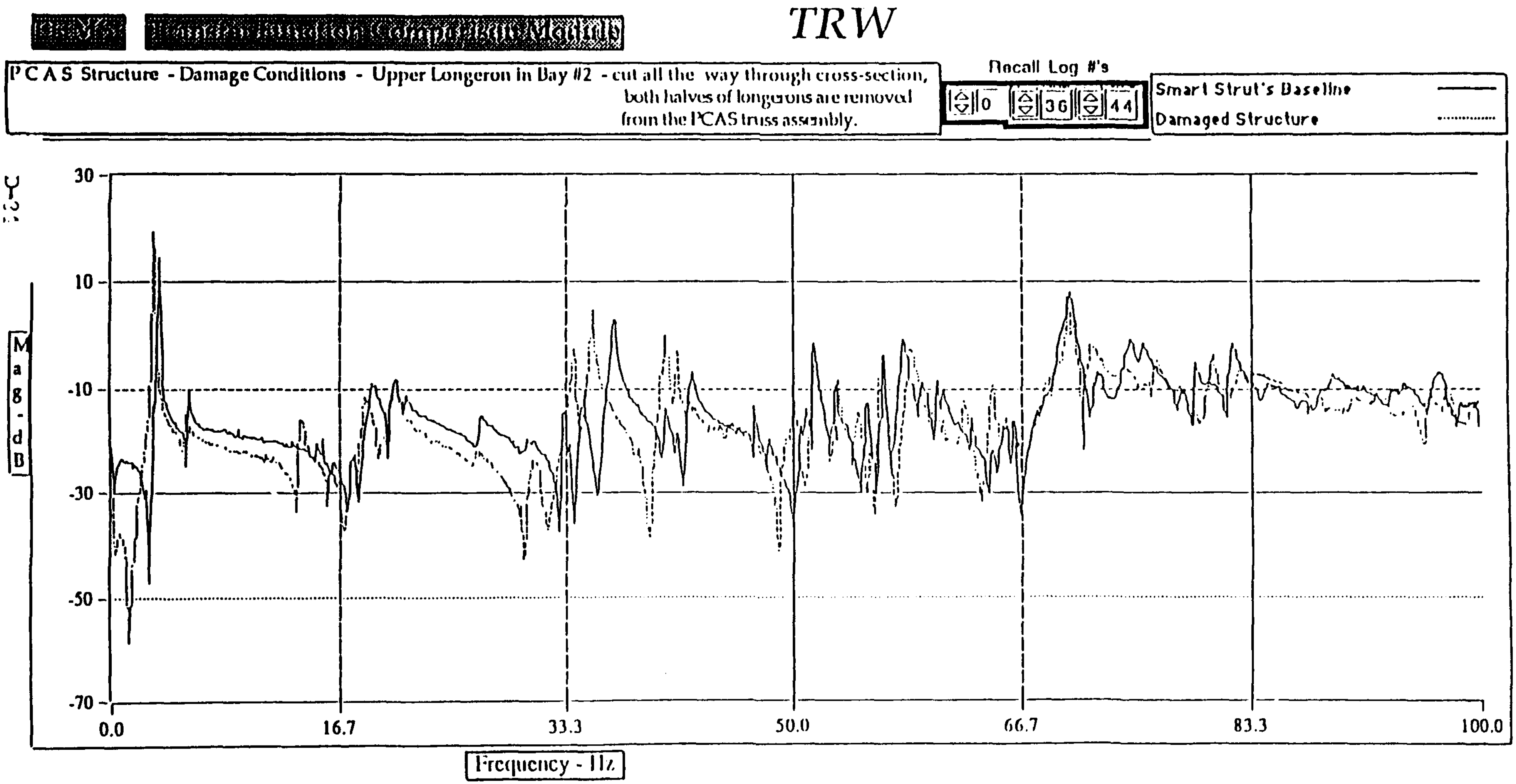
4. Smart Healing Structures

Structural Health Monitoring Sensitivity Assessment



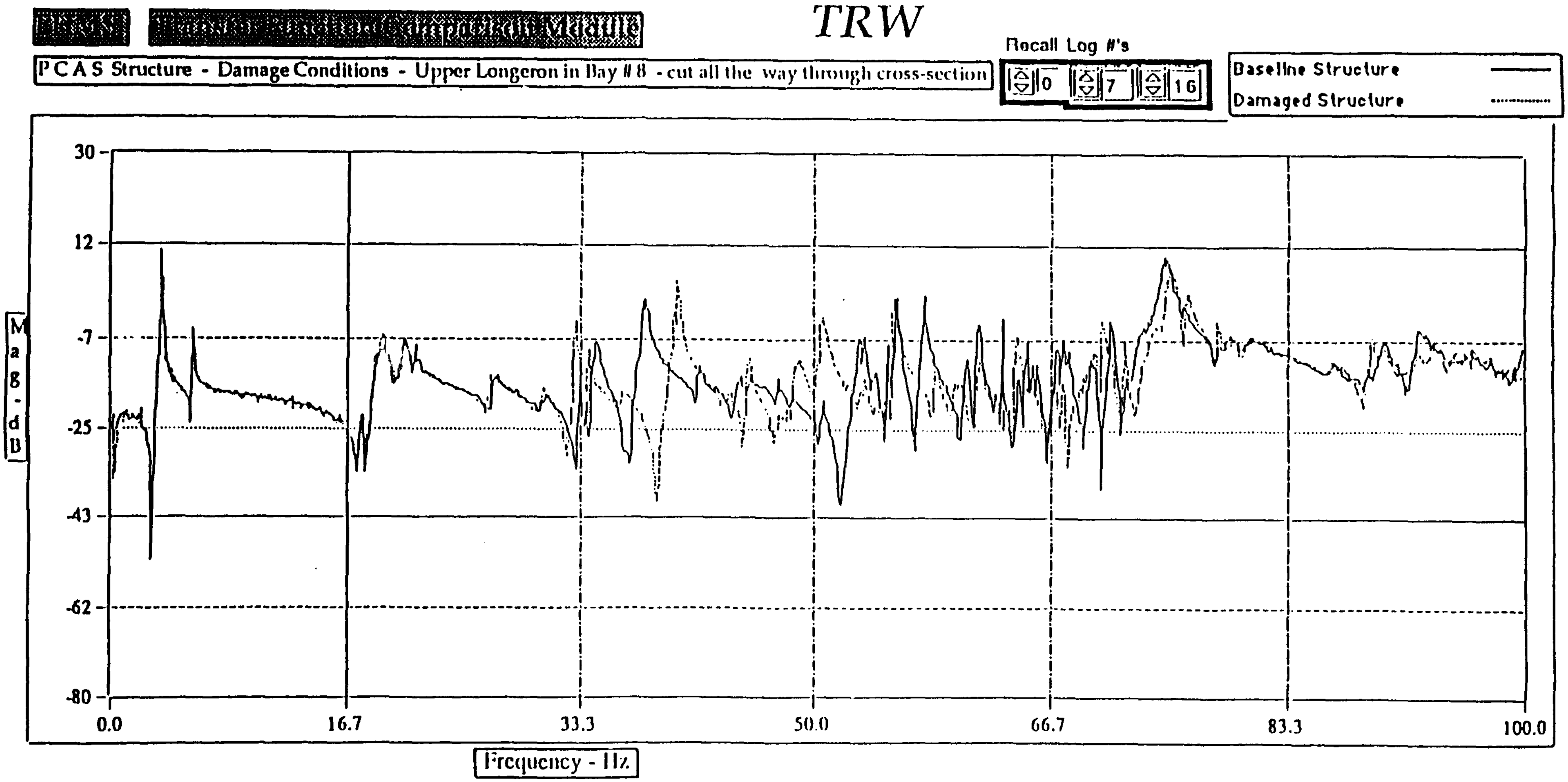
4. Smart Healing Structures

Damage to Longeron at Bay #2
(Affects both low and high frequency modes)



4. Smart Healing Structures

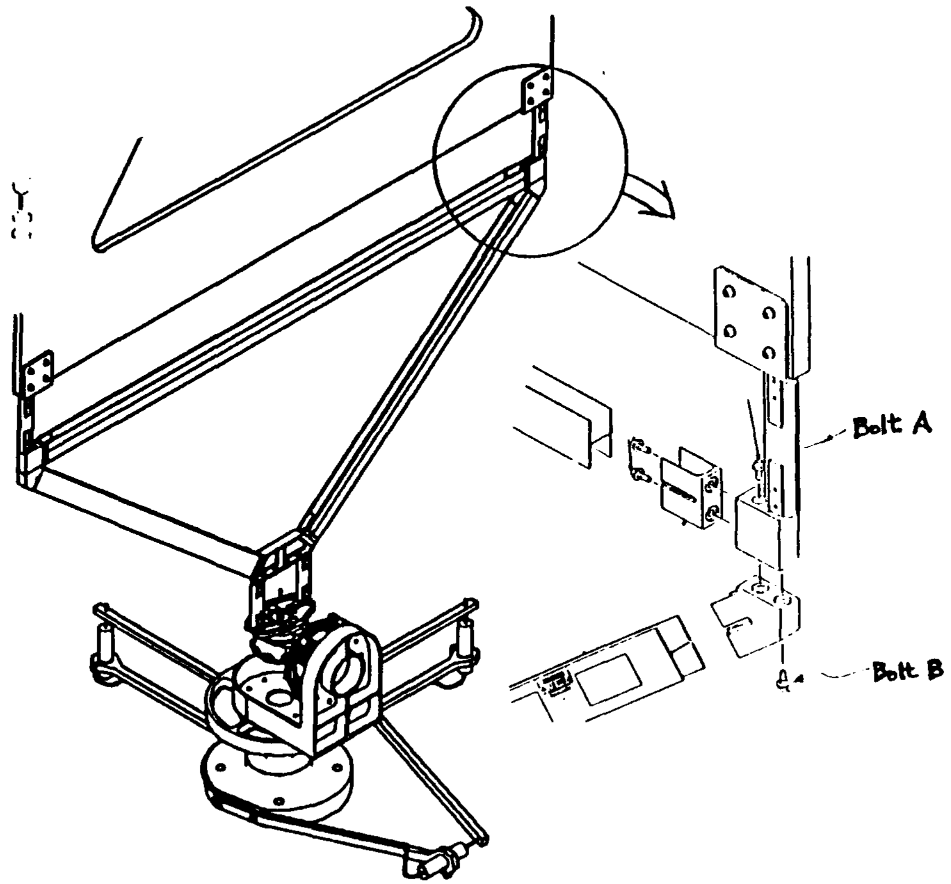
Damage to Longeron at Bay #8
(Only affects high frequency modes)



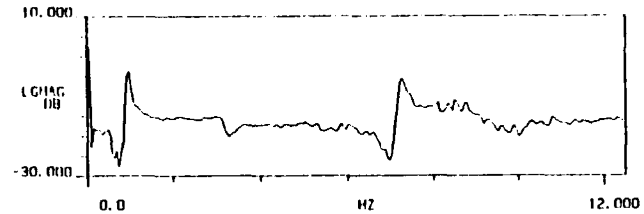
4. Smart Healing Structures

Assessment of bolted interface preloads

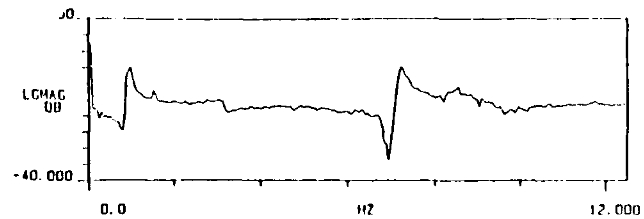
AMASS Yoke



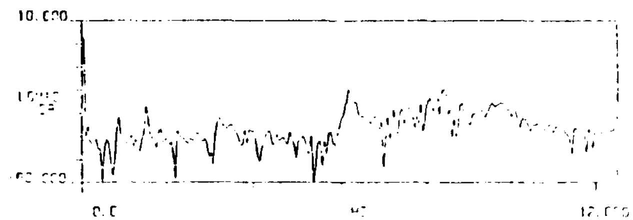
Yoke Beam to Cross Beam TF



Yoke Beam to Cross Beam TF, Bolt "A" Loose

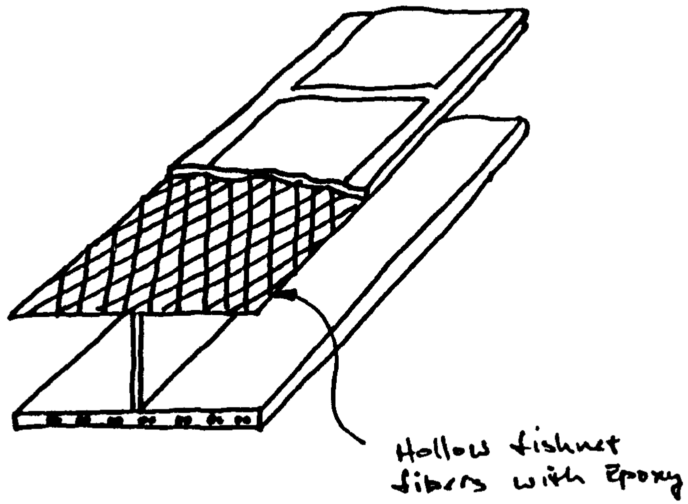


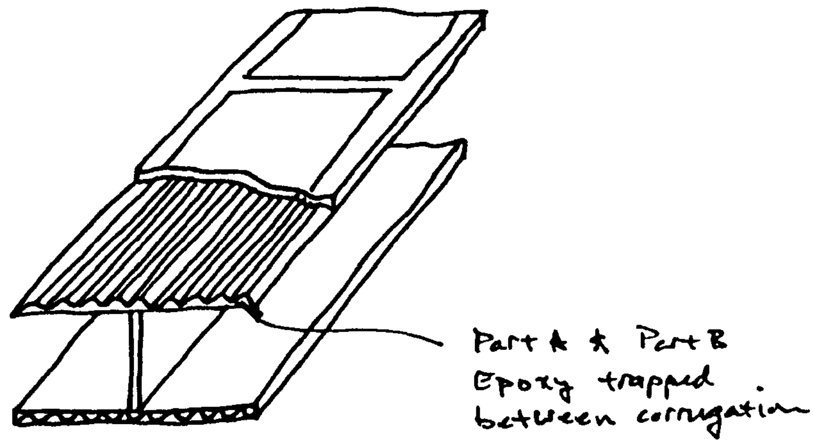
Yoke Beam to Cross Beam TF, Both Bolts Loose



4. Smart Healing Structures

- Healing a structure can be done by using embedded piezoceramic d33 effects to pump adhesives to structural break (similar to human lymph system)
- Low viscosity adhesives are available (cyanoacrylics, standard acrylics, polycyanates) approximate to water
- Two part tubing network would be embedded with PZTs
- Fault would be detected by health id, and adhesive pumping would be local microprocessor controlled





4. Smart Healing Structures

Design Status:

- Currently can detect, quantify magnitude, and globally locate structural faults

- Healing approach is only conceptual at this time, concept has been used on concrete structures

VG93-027

AN INTEGRATED SENSOR/ELECTRONICS PANEL FOR SPACECRAFT ENVIRONMENT MONITORING

A CASE STUDY FOR SAMMES LEO MODULE

P. Joshi, M. Malonson, and D. Palombo
Physical Sciences Inc.
Andover, MA

Presented at:

Advanced Sensory Spacecraft Structures Workshop
Institute of Defense Analyses
Alexandria, VA

February 10, 1993

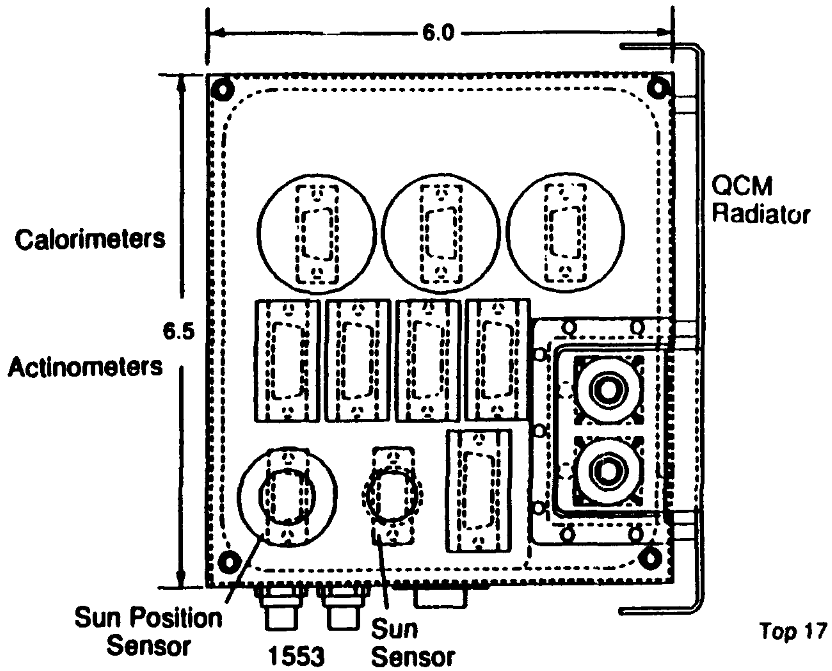
LOW EARTH ORBIT (LEO) ENVIRONMENT MONITOR MODULE FOR SPACE ACTIVES MODULAR MATERIALS EXPERIMENTS (SAMMES)

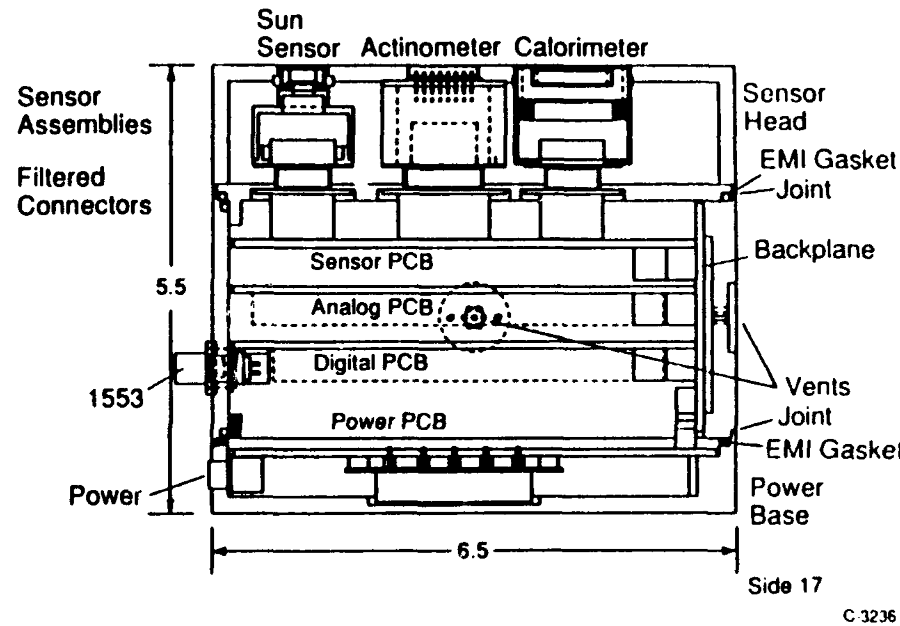
T-15141

- Function
  - Characterize LEO environment at specific locations on spacecraft
- Environment
  - AO
  - Contamination
  - Solar irradiation
  - Trapped radiation
  - Thermal cycling
- Sensors
  - Ag&C Actinometers, CQCM
  - TQCM
  - Sun sensors (irradiance and position)
  - RADFETs
  - PRTs

LEO MODULE CHARACTERISTICS

T-15142



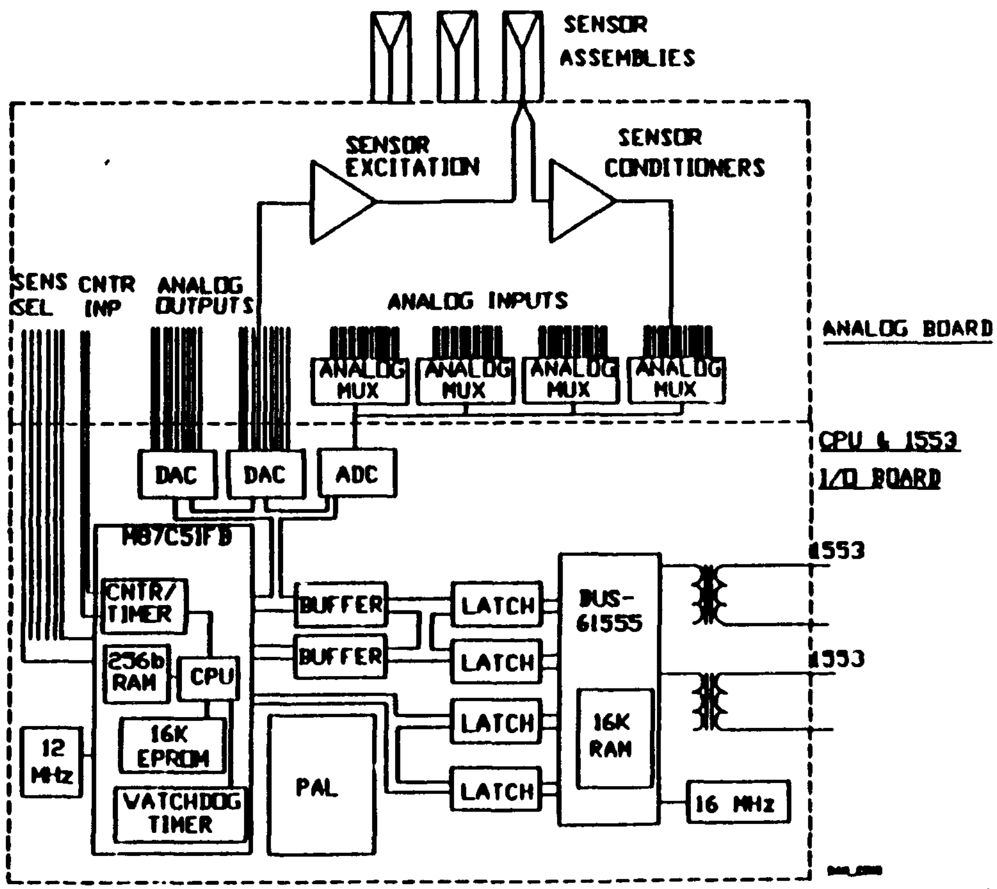


- Volume ~3500 cm 3
- Weight ~2.8 kg
  - — Housing (Mg) ~0.95 kg
  - — PCBs (incl. backplane) ~1.30 kg
  - — Hardware ~0.15 kg
  - — Sensors ~ 0.40 kg
- Weight of power board ~ 0.25 kg

- Power ~5W
- 3 yr life at 1000 km

CURRENT LEO MODULE ARCHITECTURE

T-15143



C-3237

APPROACH TO INTEGRATED SENSOR/ ELECTRONICS/STRUCTURE

T-15144

CONCEPTUAL DESIGN - I

- Conduct a case study, e.g., LEO module
  - Preserve functional/performance characteristics
  - Identify issues: Design changes, technology limitations, performance constraints, cost/risk penalties, ...

APPROACH TO INTEGRATED SENSOR/ ELECTRONICS/STRUCTURE

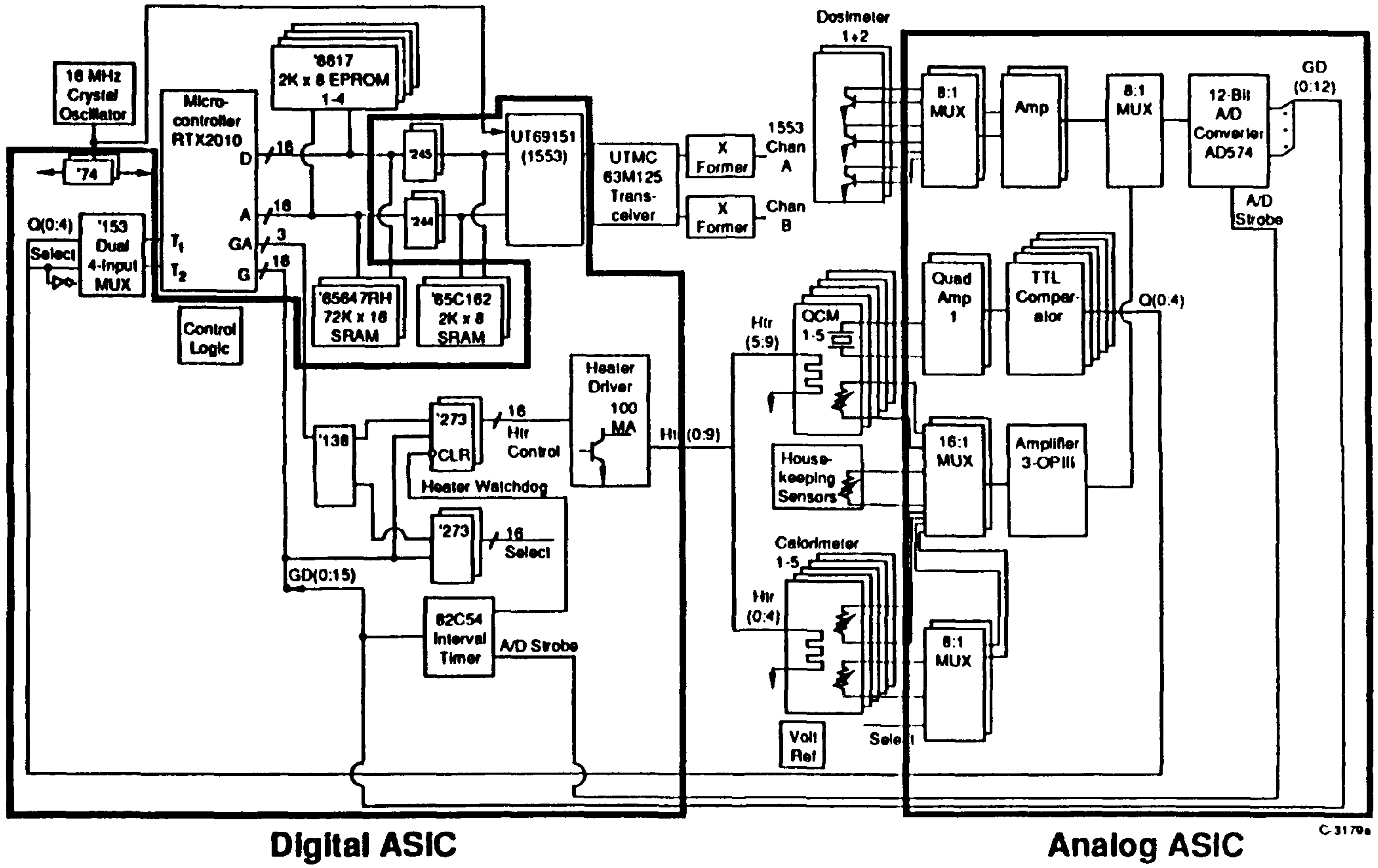
T-15145

CONCEPTUAL DESIGN - II

- Eliminate metal housing
  - — 35% of LEO weight
- Redesign electronics to regain radiation hardness
  - — Modify circuitry, reduce/eliminate "weak" components
  - — Incorporate rad hard components (Advanced Technologies)
- Miniaturize/integrate electronics into ASICs
  - — 45% of LEO weight
  - — Reduced power consumption
- Modify QCM & calorimeter designs
  - — 15% of LEO weight
  - — Plug into PCB
- Analyze structural response of G-10 board with embedded sensor/electronics
  - — Natural frequency, buckling load
  - — SAMMES protoflight random vibration spectrum
  - — Evaluate stiffening/strengthening needs
- Evaluate idea(s) on thermal control

MODIFICATIONS TO PRESENT LEO ELECTRONICS DESIGN

T-15146

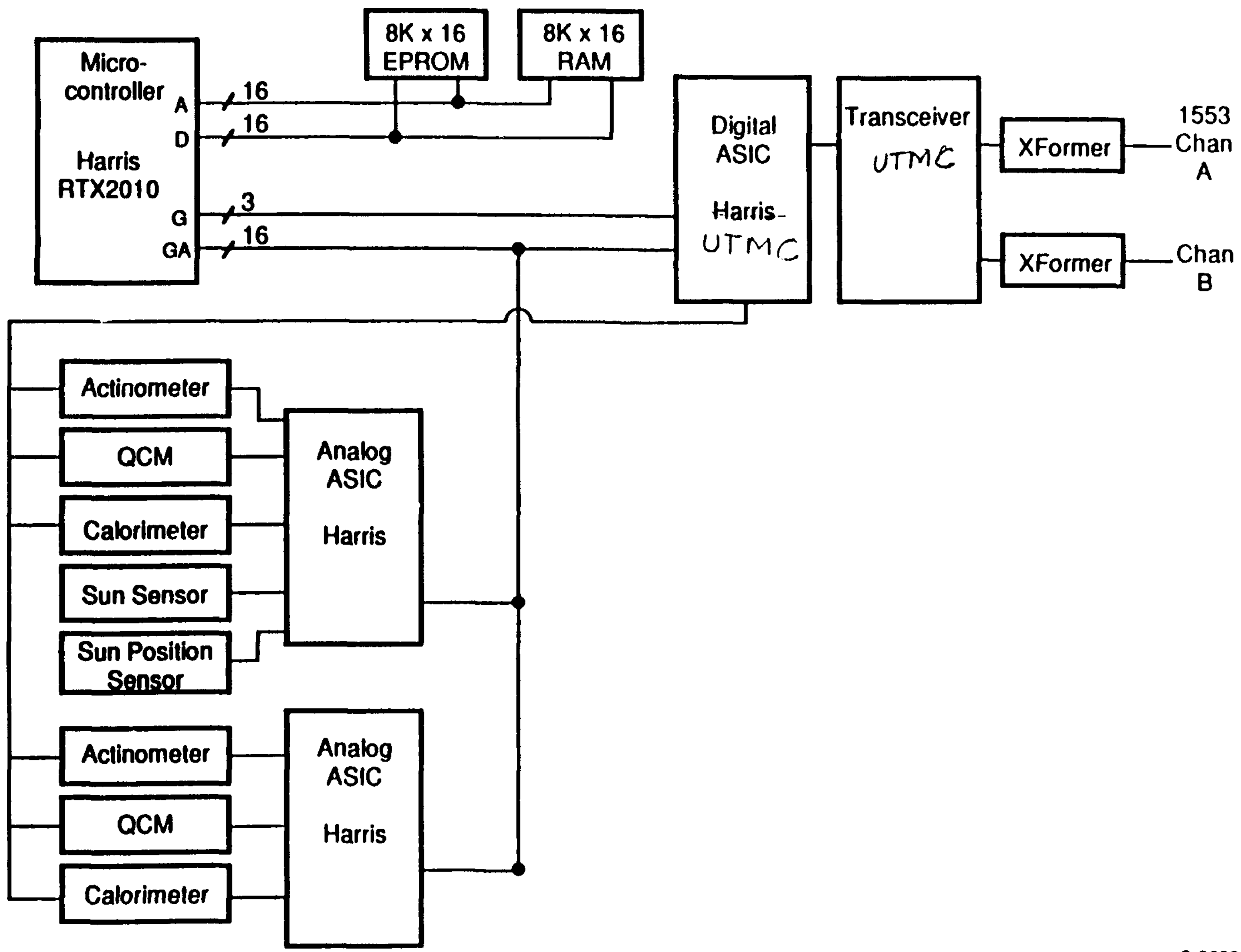


Notes: Number and types of sensors to be selected for LEO module filtered and regulated 28 VDC power available

- Components rad hard to 80 K

MINIATURIZATION OF MODIFIED LEO ELECTRONICS

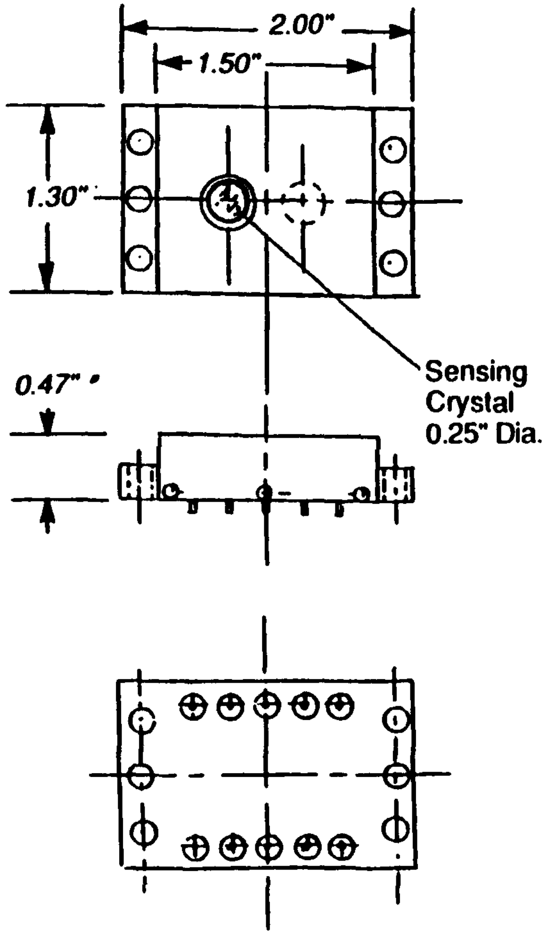
T-15147

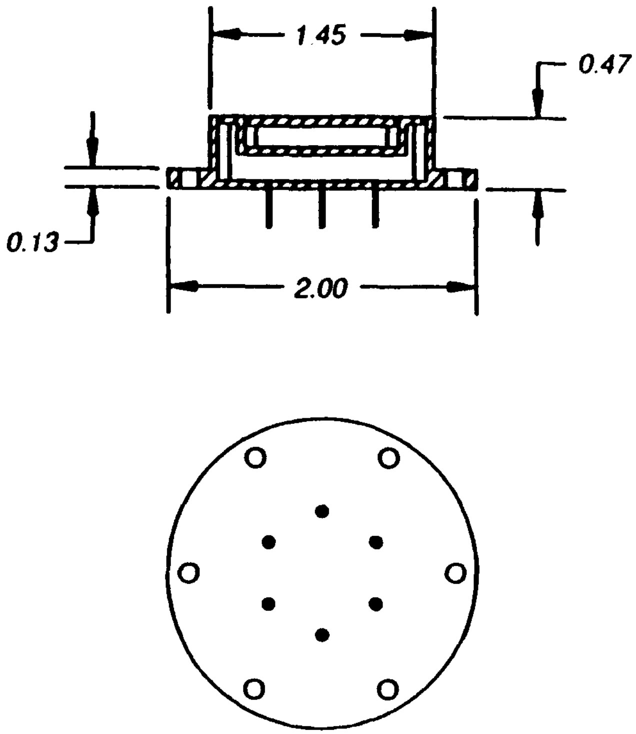


C 3238

MODIFIED COMPACT QCM & CALORIMETER DESIGNS

T-15148



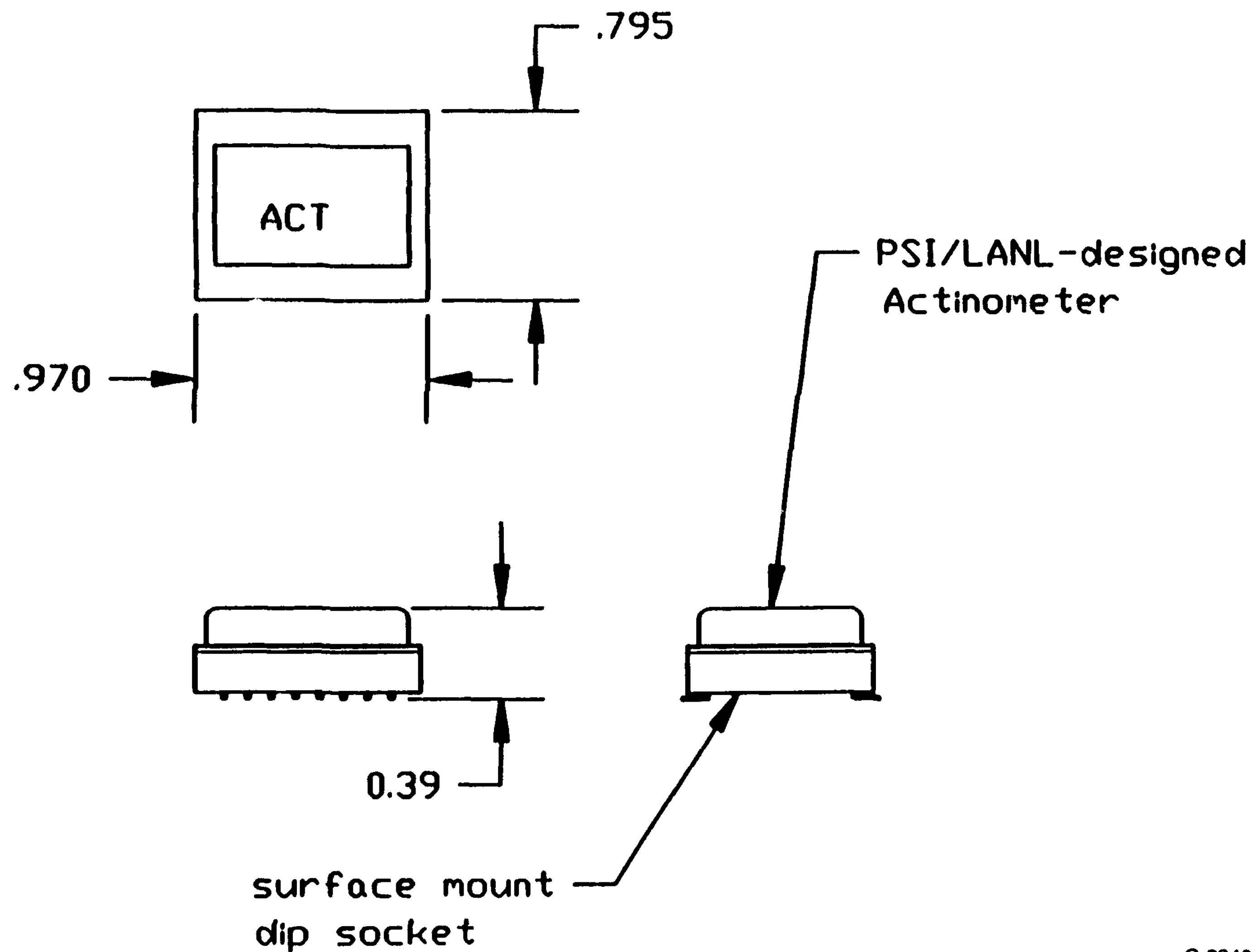


C-3239

- Basic QCM radiation-tested to 1 Mrad
- Peltier-cooled, $\Delta T = 60$ C max.
- Calorimeter not susceptible to radiation effects

SAMMES ACTINOMETER DESIGN

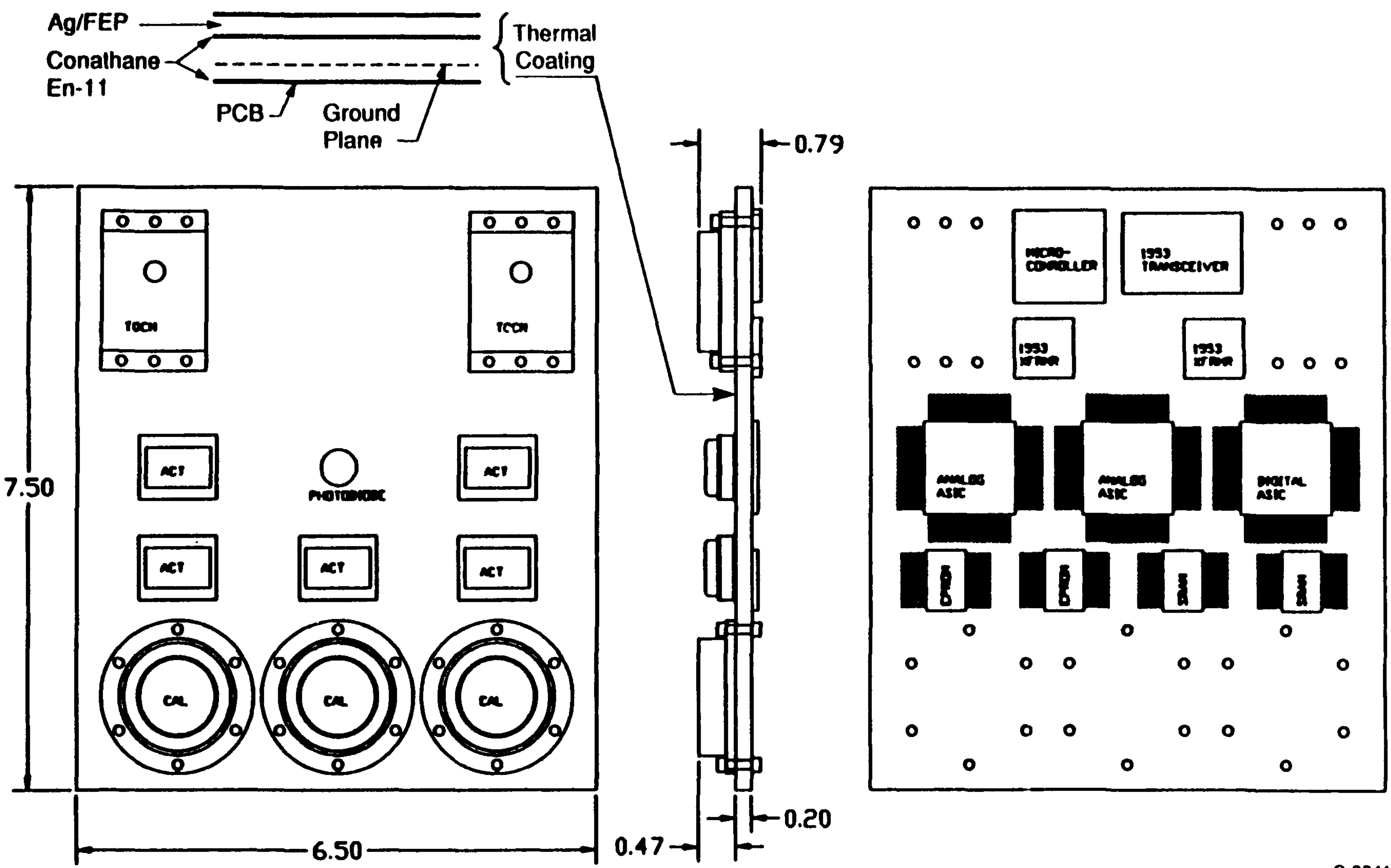
T-15149



C-3240

EMBEDDED SENSOR/ELECTRONICS PANEL

T-15150



C-3241

LEO MONITOR PANEL CHARACTERISTICS

T-15151

- Weight ~760g

G-10 PCB	290g
Components	80g
TQCMs 2 @ 60 g	120g
Calorimeters 3 @ 30g	90g
Actinometers 5 @ 13g	65g
Solder/Conformal Coating	65g
Ag/FEP film	10g
Hardware	40g
Total	760g

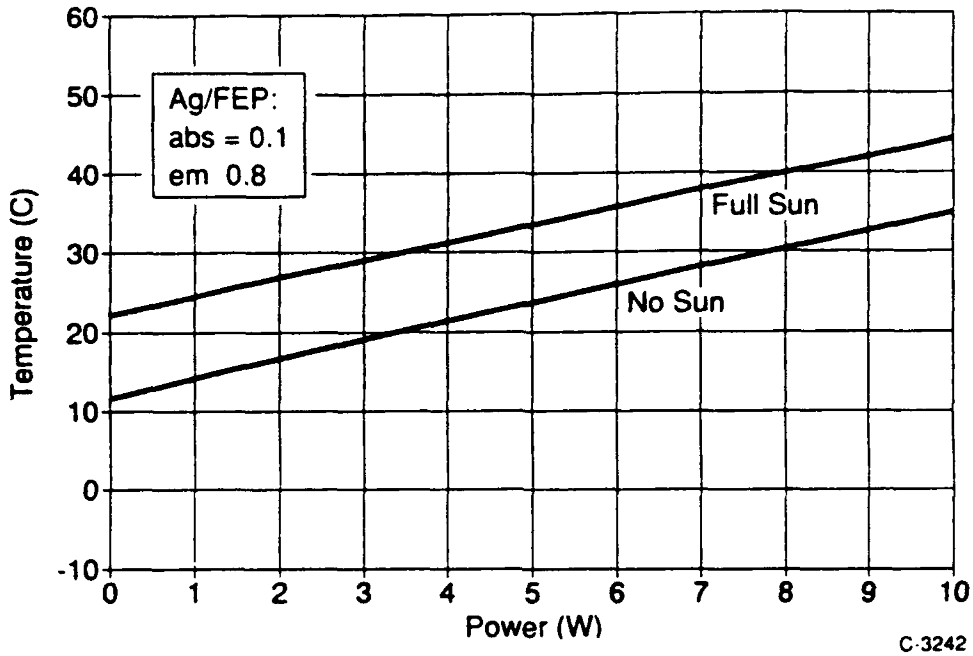
- Power
  - Electronics ~ 2.5 W
  - QCM Peltier ~4.8 W
    ~7.3 W max

- Structural Response
  - Natural frequency 167 Hz
  - SAMMES Protoflight Vibration Spectrum
    - Max stress 4925 psi (FOS=7)
    - Max displacement 0.022 in
  - Min buckling load 1520 lbs

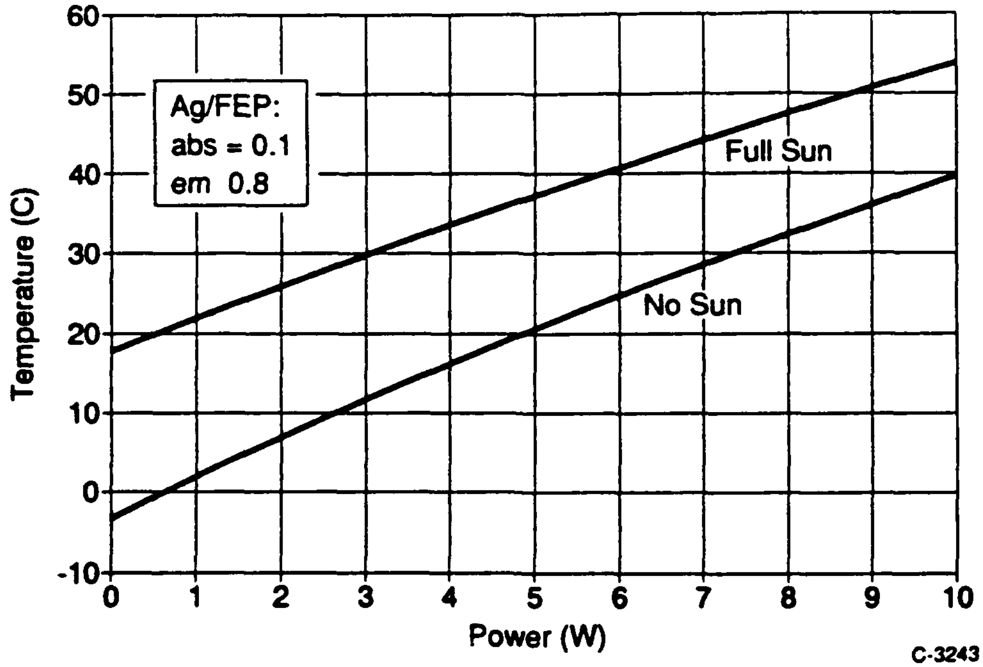
- Thermal response
  - Conduction to S/C structure may be necessary
    - Panel location important
  - Cooling QCM crystal to -25C possible under specific spacecraft conditions
    - Heat pipes may be necessary for controllable QCM cooling to <-25C

THERMAL RESPONSE OF LEO MONITOR PANEL

T-15152



a) Conduction to spacecraft
K = 0.185 W/K, $T_{S/C}$ = 27 C



b) No conduction to spacecraft

PSI

SUMMARY AND ISSUES - I

T-15153

- Performance gains/sacrifices
  - Reduced weight by ~70%
  - Sacrificed quiescent (low power) mode of current LEO design, but reduced operating power by 2.5 W (5 W → 2.5 W)
  - Gained radiation hardness to 80 krad (Si), permitting operation to higher altitudes, hostile environments – life ?
  - Lost some controllability over cooling QCM crystal to < -25C
- Detailed structural analysis TBD
- EMI susceptibility not evaluated

SUMMARY AND ISSUES - II

T-15154

- Thermal control issues
  - — For effective conduction to S/C, PCB construction with >5 mil thick ground plane
  - — Use of heat pipes
    - Type and geometry
    - Weight impact
  - — Advanced active control techniques, compatible with panel construction, need evaluation

- Cost issues
  - — Development tools and NRE costs for ASICS high ~0($$10^5$)
  - — ASICS reproduction costs reasonable ~0 ($$10^2$)
    - Routine incorporation of environment monitor panel into S/C structure
  - — S/C integration highly simplified, save $
  - — Reduction in space qualification costs
    - After full qual testing of first few panels, sample testing from a lot may be sufficient
    - Acceptance testing at spacecraft level